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AH-64 FLIGHT AND WEAPONS SIMULATOR CONCEPT FORMULATION STUDY. V--ETC(U)
SEP 77 J L DICKMAN, H KESTENBAUM, P W CARO   N61339-77-C-0048
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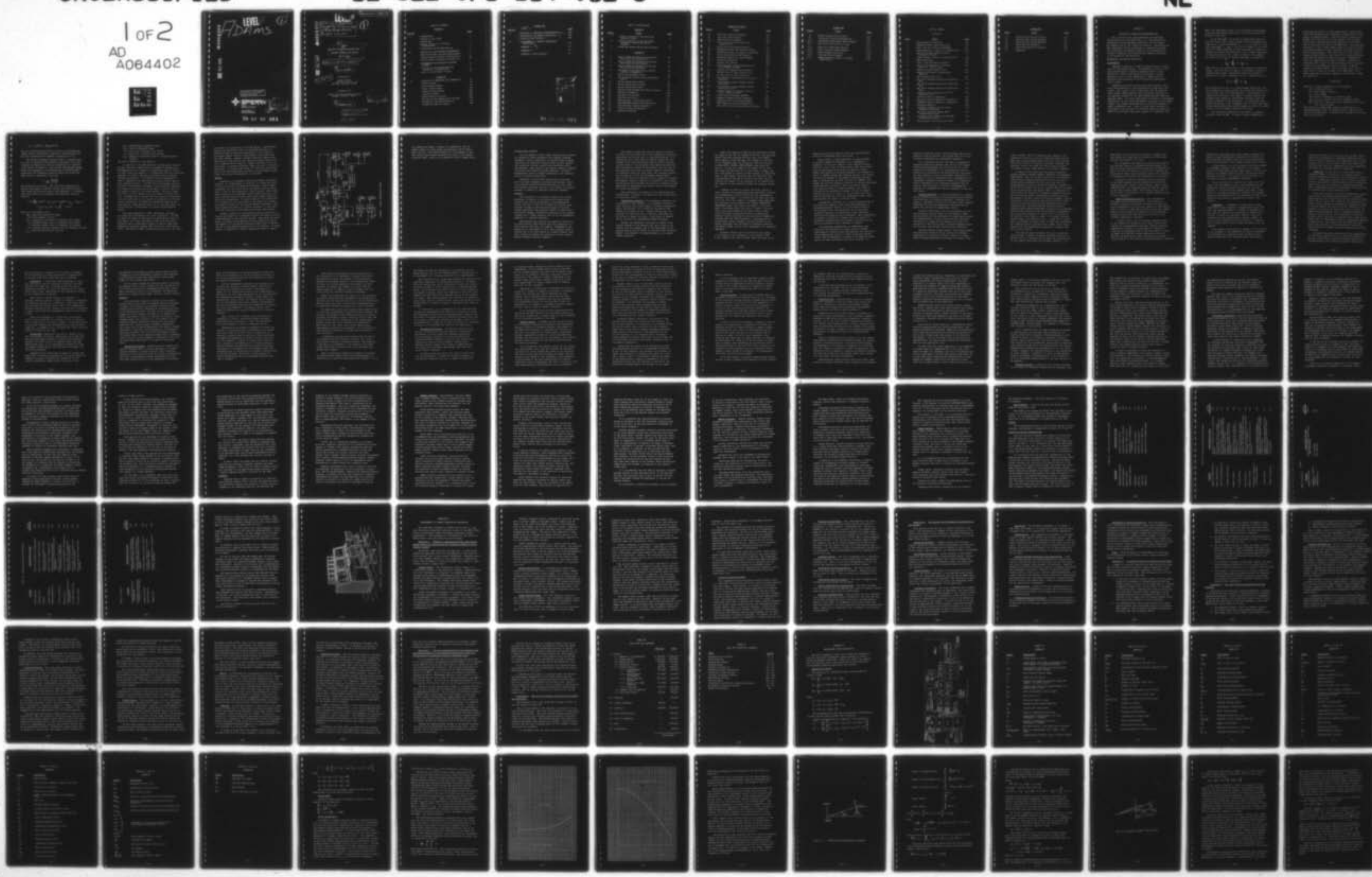

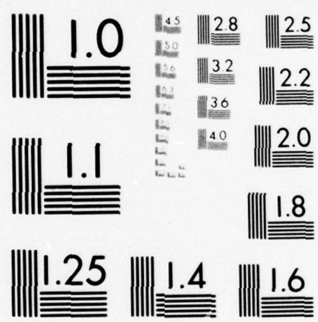

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(14) SE-622-CFS-114-VOL-3

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FLIGHT AND WEAPONS SIMULATOR

CONCEPT FORMULATION STUDY.

Volume III.

(15) N61339-77-C-0048

(9) Final Report,

(12) 113 p.

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Orlando, Florida 32813

(11) Sep~~tember~~ 1977

393 444

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SECTION V

ANALYSIS OF OPERATING CHARACTERISTICS

This section of the study addresses the operating characteristics of the AH-64 FWS, i.e., the simulation of aerodynamic motion and engine operation, and the design and capabilities of the instructor station. Conclusions are made regarding possible approaches to mathematical models for aerodynamic and engine simulation; and regarding the controls, displays, and instructional programs considered to be optimum for the AH-64 FWS.

AERODYNAMIC AND ENGINE SIMULATION

Aerodynamics

Appendix A presents a complete equation set for simulation of a helicopter motion. The appendix is based on the Sperry-SECOR Specific Response Approach (SRA) to rotor simulation. Much of the equation development, however, applies as well to other approaches in common use and underlies the discussion of the differences among models, which follows.

Mathematical models of helicopter motion differ from each other primarily in their description of the main rotor system. Most current rotor simulations take the modified blade element (MBE) approach, the coefficient approach, or the approach typified by the Sperry-SECOR Specific Response Approach (SRA). All three approaches are founded on developing expressions for the forces and moments acting on a rotor-blade element, the element being defined as an airfoil segment at polar coordinates r, Ψ. Here r is the radial distance of the element from the center of rotation along the blade axis and Ψ is the azimuth angle with respect to a reference axis.

Where the approaches differ is in the method of proceeding from the blade-element quantities to the total forces and moments of the rotor.

In the MBE model, for which the theoretical basis is given by Toler (1963), blade element forces and moments are computed at i radial distances $r_1, \ldots, r_i$ at each of j azimuth angles $\psi_1, \ldots, \psi_j$. The force or moment on the rotor blade at azimuth angle ψ_j is then computed by a numerical integration scheme, which derives it as a linear combination of the quantities at the i radial stations. For example, the thrust (lift) T_{ψ_j} at azimuth angle ψ_j is computed as

$$T_{\psi_j} = \sum_{n=1}^{i} k_n \; T_{\psi_j}, r_n$$

where the k's are coefficients of the numerical integration scheme. With the force or moment on the blade at each of j azimuth angles known, integration around the azimuth is effected by a linear combination of the j quantities; e.g.,

$$T_{total} = \sum_{m=1}^{j} k_m \; T_{\psi_j}$$

The computation of the i X j blade-element quantities, and the integrations along the blade and around the azimuth, are done in real time in the MBE approach. Consequently, for computation efficiency, the number of radial stations and azimuth angles should be the minimum consistent with the accuracy required of the simulation. A recent NASA study (Houck and Bowles, 1976) recommends that no fewer than three radial stations and three azimuth angles be used in the simulation of an articulated single rotor system.

The coefficient approach on the surface is markedly different from the MBE. It bears a closer resemblance to

fixed-wing simulations in that dimensionless coefficients of forces and moments are obtained by interpolation in data tables in computer memory. The data tables, however, represent the output of an off-line program (the so-called "Truth Rotor" program) which incorporates a rotor model that is basically the same as the MBE model. The principal difference is that a much higher number of radial stations and azimuth angles are used, typically 30 radial stations and 72 azimuth angles. With the increase in the number of computed blade-element values, errors in integrating along the blade and around the disk are reduced. Furthermore, since the computations are done off-line, no penalty in computing time is paid for the increased accuracy (provided an efficient interpolation method is used). Computer storage is another matter: the data tables alone may require several times the storage of the MBE model. In a model using the coefficient approach, rotor thrust T might be computed as

$$T = k\sigma\Omega^2 C_T$$

where k = constant depending on rotor geometry

σ = air density ratio

Ω = rotor angular velocity

$C_T = f(\mu, \lambda, \theta_E)$

μ = ratio of airspeed to blade-tip speed

λ = ratio of in-flow velocity to blade-tip speed

θ_E = effective blade pitch angle (dependent on collective stick setting)

The function of $f(\mu, \lambda, \theta_E)$ might be represented by a three-dimensional table in computer memory, and C_T calculated by interpolation. Alternatively, C_T might be factored into a form such as:

$$C_T = f_1(\mu,\lambda) + \Theta_E f_2(\mu,\lambda)$$

The two functions would then be stored as two-dimensional tables and the coefficient computed by interpolating twice and then evaluating the algebraic expression for C_T.

The Specific Response Approach (SRA) is characterized by a set of equations which describe helicopter rotor performance and reaction by directly computing the composite rotor forces and moments. With certain simplifying assumptions (see Appendix A), the expressions for blade-element quantities are integrable along the blade and around the disk; that is, equations of the form

$$T = \frac{1}{2\pi}\int_0^{2} d\psi \int_0^{R} dT$$

have analytical solutions. The simulation equations for thrust, flap angles, in-plane forces, and induced and profile torque can be derived from such equations. To continue with rotor thrust as an example, the simulation equation would be

$$T = \sigma\left[\Theta_E\,(k_1\Omega^2 + k_2\,V_{xy}^2) + k_3\Omega(W - W_{i_m} - U\,B_{1S} - V\,A_{1S}) + k_4\,(pU + q_1\,V)\right]\quad f\,({}^{L}ss)$$

where σ = air density ratio

Θ_E = effective blade pitch angle

Ω = rotor angular velocity

V_{xy} = airspeed in X-Y plane of reference axis system

U = airspeed along X axis of reference axis system

V = airspeed along Y axis of reference axis system

W = vertical velocity (along Z axis of reference system)

W_{i_m} = mean induced vertical velocity

B_{1S} = longitudinal swashplate angle
A_{1S} = lateral swashplate angle
p = roll rate, reference axis system
q_1 = pitch rate, reference axis system
L_{ss} = length of slipstream (used to introduce ground effects)

and the k's depend on rotor geometry.

In contrast to the MBE approach, the SRA model requires neither real-time computation of incremental variables nor the application of a numerical integration scheme to arrive at total forces and moments. In comparison with the coefficient approach, it offers continuous solutions and low computer storage requirements. It differs from both approaches in that it depends on the mean induced velocity rather than on local induced velocity. The MBE real-time program, and the off-line ("Truth Rotor") program of the coefficient approach, both depend on defining the local angle of attack, that is, the angle of attack of the blade element. The local angle of attack, in turn, depends on local induced vertical velocity. Although any of several in-flow velocity distributions over the rotor disk can be assumed in attempting to develop a rotor simulation, no definitive simulation equation has been derived. Mean induced velocity, on the other hand, can be derived with a high degree of accuracy from momentum theory.

All three approaches -- MBE, coefficient, and SRA -- are being used successfully for rotor simulation. The MBE is used in a number of helicopter training devices built in the 1960's; it is also the basis of the rotor simulation currently used in helicopter studies on the RTS (Real-Time Simulation) system at Langley Research Center, NASA (Houck, 1974). Helicopter flight training devices built in the 1970's

use either the coefficient or the SRA method. Sperry-SECOR prefers the SRA method, which it developed and which is currently used in real-time simulations of more types of helicopter (HH-3F, HH-52A, CH-3E, HH-53C, and TH-1L) than any other method. However, another simulator manufacturer, throwing into the balance such factors as model characteristics, computer system capacity, support software, and -- in particular -- in-house expertise, might well have a different preference. So long as the design is carefully constructed, any of the three approaches can lead to an aerodynamic model within the accuracy requirements of the AAHT.

Engines

Simulation of turboshaft engine performance and dynamic response, to a high degree of accuracy, is within the state of the art of real-time modeling techniques. Sperry-SECOR recommends that the structure of the engine model be analagous to that of the engine/fuel control system. While other model structures may reproduce normal engine operation with equal fidelity and efficiency, the system analog simplifies malfunction simulation. It permits many of the malfunctions to be inserted at only one entry to the model, yet produce the expected results on all affected engine variables. With other model structures, it is often necessary to force malfunction reactions on each affected variable individually.

Figure 45 shows the relationships among variables in a typical math model of a turboshaft engine, the model structure being analagous to the aircraft system. Also shown are entry points for some of the malfunctions that might occur while the engine is in the normal operating range (idle or above). The key to the numbered malfunctions is as follows: 1) engine surge; 2) flameout; 3) turbine temperature high; 4) engine

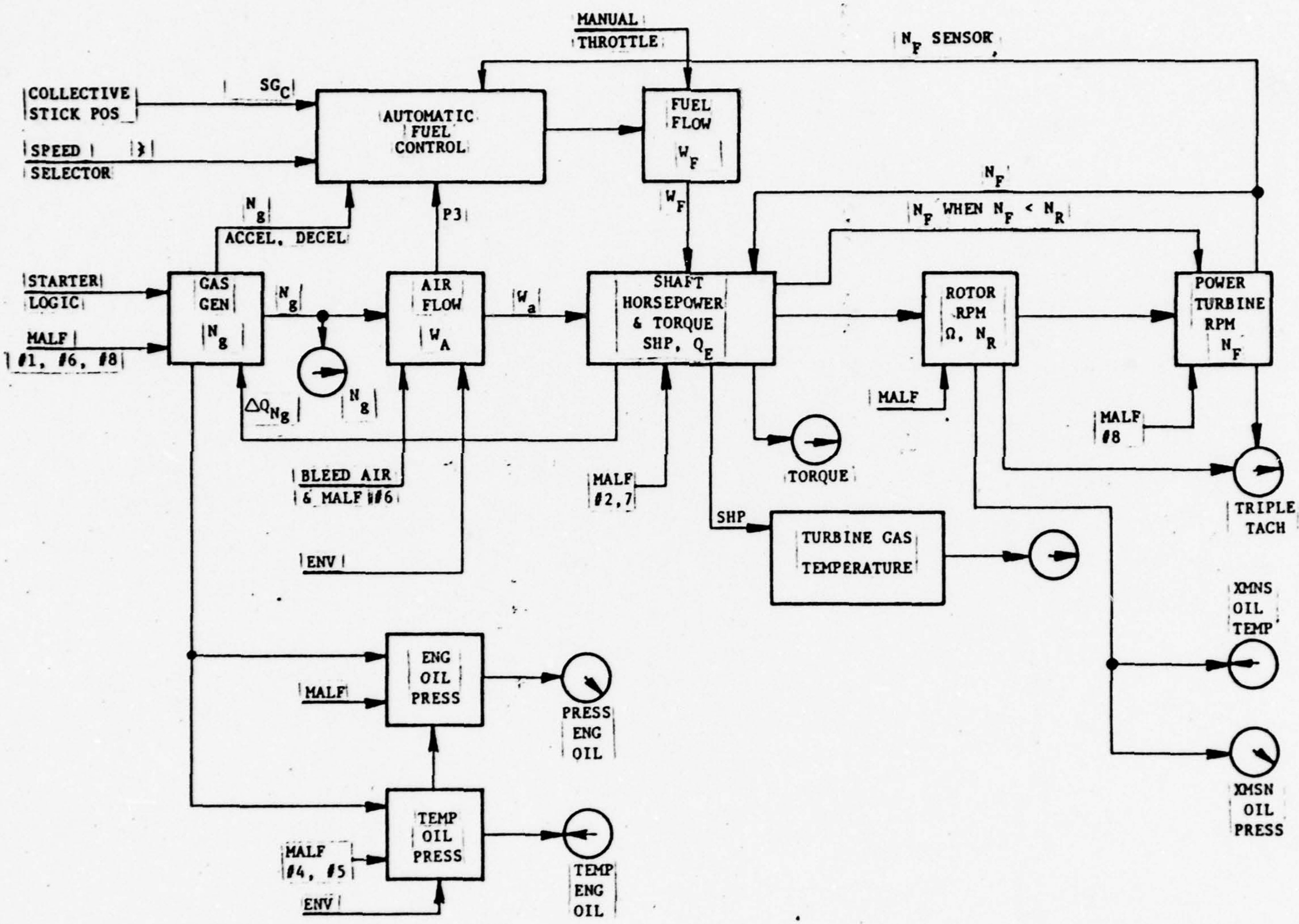


FIGURE 45. ENGINE COMPUTATIONAL SYSTEM

oil temperature high; 5) engine oil temperature low; 6) engine icing; 7) torque gauge fluctuations; and 8) tachometer failure. The surge malfunction is an example of one that affects many engine variables but that, in an analog-structure model, needs to be inserted at only a single point.

INSTRUCTIONAL SYSTEMS

For the purpose of this study, instructional systems are defined as those equipments and computer programs intended to assist instructors to perform their training tasks with the simulator. Instructional systems include the instructor station controls and indicators, CRT's and displays, input devices, and various computer programs to initiate and control training exercises, introduce malfunctions, monitor student performance, and otherwise provide or assist instruction.

Generally, instructional systems may be divided into two broad categories: hardware and software. There is an obvious interrelationship between the two, since the controls and input devices in the trainer are usually designed to operate or implement software programs.

Controls

The controls at an instructor station can include momentary, alternate, or latching action push-button switches that may be illuminated or non-illuminated; rotary controls to vary the intensity of effects; slew switches to make uni-directional changes in aircraft flight conditions; and joystick controls to make multi-directional changes. Push-button switches can be grouped together for a common purpose, such as in an alphanumeric keyboard or a function keyboard.

Some specialized controls are sometimes referred to as input devices, particularly when their purpose is to enter digital data into the computer. Alphanumeric keyboards can be considered to be in this category. Such a distinction is not very useful in a modern trainer, however, because virtually all instructor station controls operate through a digital computer.

The extent to which any type of control is used in a trainer can be either left to the contractor's option or prescribed, in various ways, in the specification. It is considered that if any type of control clearly has advantages over other types that could be used to perform a given function, the preferred type should be specified. This conclusion is based on the premise that the cost of the preferred type will be within a range of acceptable or reasonable costs for such items. The rationale behind the conclusion is that the Government should insure that it will receive a desired level or quality of trainer performance. Being as explicit as possible in the trainer specification will decrease the risk of a contractor using approaches or equipments that reduce costs at the expense of trainer performance.

The following is an analysis of the advantages and disadvantages of using in the AAHT each type of potentially available control.

Alphanumeric Keyboard. An alphanumeric keyboard, for the purpose of this analysis, is a standard typewriter-style keyboard with a full range of letters, punctuation marks, and numerals. It is normally provided by CRT vendors as an input device. Usually special keys are provided for functions such as RUB OUT, LINE FEED, etc. By the use of upper case keys, a wide range of symbols can be available for programming graphic displays.

Whether an alphanumeric keyboard is needed on any trainer depends on the quantity and type of data to be entered into the computer and on the philosophy of formatting inputs. Device 2F108, an A-4M OFT build by Sperry SECOR, is an example of strong dependence on an alphanumeric keyboard.

Almost all inputs are made by the instructor calling up a page on the CRT (by typing the letter P and the page number) and then entering the data via a line number which appears on the CRT page. For example, to add fuel to the fuselage tank, the instructor calls up the page entitled FUEL, OXYGEN, EMER CONTROLS, and types the letter I (a code for "input"), the number of the line that reads FUS QTY (line 01 in this case), a comma, and the total number of pounds of fuel desired. To refuel the tank to 1500 pounds, the entry will be "I01,1500." The entry appears on the CRT on an edit line where the instructor can inspect it for accuracy; it is entered into the computer by the instructor using the carriage return key.

A number of yes-no or on-off functions, which on other trainers are accomplished with push-button switches, are accomplished in Device 2F108 with the alphanumeric keyboard. The number 1 is entered for the true state and 0 for not true. For example, to program icing conditions, the instructor first displays the INITIAL CONDITIONS, ENVIRONMENT page, then enters the number 1 in line 28 which is entitled ICING. The entry is "I28,1." To later remove the icing condition, he types "I28,0." Other on-off functions accomplished with the alphanumeric keyboard include starting the mission clock, loading the internal guns and chaff dispensers, installing and removing wheel chocks, engaging the probe/drogue in in-flight refueling, and resetting the emergency generator and manual flight controls after employment in a simulated emergency.

In Device 2F108, only five letters (P for "page," I for "input," F for "failure," D for "delete," and R for "repeat") are used in input codes, but most of the

remaining letters are used to enter the identification letters of programmed radio facilities.

Device 2F119, an EA-6B WST built by Sperry SECOR, is another example of dependence on an alphanumeric keyboard. In this case, inputs to the computer are preceded by a one-, two-, or three-letter code which identifies the data being entered and its purpose. Unlike 2F108, this method is not page dependent. For example, an entry of "HD360" during the training exercise will change the aircraft heading to 360 degrees regardless of what page is displayed on the CRT. An entry of "IHD360" will change the aircraft heading on the set of initial conditions being modified. One-letter codes are used for inputs that require brevity for rapid entering. The letter B, followed by the malfunction number, is used to begin a malfunction and R to remove it. As an instructor aid, a page is provided that lists all permissible input codes. Approximately 80 separate codes are used.

Alphanumeric keyboards are a very flexible method of accessing the computer. With either page-dependent or non-page-dependent formats, as in the Device 2F108 or 2F119 respectively, the instructor can be provided a tremendous capacity for performing trainer operating functions and problem control procedures. Most importantly, if methods of instruction change after the trainer is delivered, modifications can be made in displays and instructor procedures with a minimum of expense.

The principal disadvantage in alphanumeric keyboards is the difficulty in typing entries. Formats consisting of several letters and numerals are relatively time-consuming and liable to result in mistakes during typing. This disadvantage is reduced with improved typing skill, but most instructors are not so inclined. It

should be noted that Device 2F108 normally uses both an instructor and an operator, the latter able to be well trained in operating the alphanumeric keyboard.

It is concluded that for the AAHT an alphanumeric keyboard would be a suitable input device, the typing problem notwithstanding, but in this case it is considered that providing it at the instruction station should not be required by the specification. The reason for this opinion is that an acceptable alternative is available, as will be discussed later. Consequently, the alphanumeric keyboard should be viewed as a contractor option, dependent on the formatting approach that he selects. Also pertinent is whether an alphanumeric keyboard or teletypewriter will be available in the computer area.

Function Keyboard. A function keyboard is a grouping of push-button switches that perform various discrete functions such as calling up displays, "freezing" the trainer, overriding a crash, etc. In some cases, separate keyboards are used for homogeneous functions and the panels are labeled with appropriate titles.

In Device 2F108 there are two such panels, one for the instructor and the other for the operator. Push-button switches at the instructor's control panel operate the communications, freeze, crash override, and reset functions. On a panel at the operator's station are switches for the motion system, simulated oxygen system, X-Y recorder, and aircraft position slew functions.

The B-52 digital flight trainer, which Sperry SECOR has delivered to the Air Force, has an even simpler arrangement of instructor controls. There is a single panel containing push-button switches for freeze, reset,

crash override, and five communications channels; two push-button switches to turn on simulated ground service pumps and a hatch warning light; and three slew switches for on-line control of aircraft latitude, longitude, and altitude. Also on the panel are three rotary controls for headset volume, sound effects, and console lighting.

In Device 2F119 there are four panels designated MISSION CONTROL, TRAINER CONTROL, FUNCTION, and AIRCRAFT/COMM CONTROL. Each of the three instructors has different combinations of panels, appropriate to his own area of instructional responsibility. The functions that are switch-operated in Device 2F108 are similarly operated in Device 2F119, except for the X-Y recorder which is replaced in the EA-6B trainer with graphic CRT's. In addition, in Device 2F119 the functions of applying simulated starting air and external power, installing and removing chocks, performing a catapult launch and arrested landing, zeroing the mission clock, selecting and entering initial condition sets, selecting and starting demonstrations, performing replay, and selecting and starting computer-evaluated (performance-measuring) missions are accomplished with switches located on the various panels. Furthermore, all of the basic displays in Device 2F119 are called up by switches on the function panel. If a display contains several pages, the instructor uses a paging key to increment or decrement the pages until he finds the one desired. As a back-up method, each page has a number which can be entered with the alphanumeric keyboard in a manner similar to Device 2F108.

The function panel on Device 2F119 has 32 keys and uses overlays to permit assigning different functions to any key. Up to 16 overlays can be used, hence theoretically 512 separate functions are available. However, it is

undesirable for the instructor to have to change overlays during any single mode of operation, so only four overlays are planned to be used.

It is apparent that function switches solve many of the problems inherent in keyboard-entered formats. Not only are switch operations faster and less susceptible to error, but the fact that each switch can be labeled and located with other related switches assists an instructor in remembering procedures and organizing his activities.

Certainly a function keyboard should be provided on the AAHT. Hardware controls should be provided for operating motion, freeze, crash override, reset, intercommunications, and emergency power-off and for calling up the basic display pages. The overlay system used in Device 2F119 is considered to be somewhat cumbersome and is not recommended.

Numeric/Alphanumeric Matrix. Most alphanumeric keyboards can be purchased with a 12-key matrix of switches containing ten digits and two extra keys that can be programmed to type various symbols or punctuation marks, of which a comma and a period are the most common. Such a matrix enables an instructor to enter numerals somewhat faster than with the top row of keys on the standard alphanumeric keyboard.

A numeric matrix can be purchased separately and, if the formats are designed to be simple, can be used instead of an alphanumeric keyboard, thereby achieving significant economy if a large number of trainers is involved. By programming one of the extra keys to select an upper case function, eleven additional letters or punctuation marks can be added, resulting in an input device similar to that used in airborne navigation computers.

Furthermore, additional keys can be added, producing, in effect, a small alphanumeric keyboard. Device 2B33, the AH-1Q OFT built by Singer Link, has such an input device with 16 keys (without a full range of upper case letters).

A 16-key matrix (or one of similar size) has a number of advantages, besides costs. Because of its compact size, it is especially suitable where space is restricted; and with its limited number of keys, particularly those containing letters, it is easier for an instructor to use than a full-size alphanumeric keyboard.

It is concluded that a matrix with upper case functions, with the number of keys to be determined by the contractor, would be entirely suitable for the AAHT. However, it is believed that whether this type of input device or a standard alphanumeric keyboard is furnished should be discretionary with the offerors; and the trainer specifications should be appropriately broad on the subject.

Thumbwheel. A thumbwheel or digiswitch is sometimes used to input numbers. To handle multi-digit numbers, the required number of switches is arranged in a row, thus the capacity of this method is limited, practically, to three- or four-digit entries. After the switches have been manipulated to select a number, it can be easily inspected to insure accuracy. A separate key or switch must be used to enter the number into the computer.

This method of data entry is useful if it is desired to set a number in the thumbwheel and have it available for reference for a period of time. In Device 2F119, initial conditions sets, demonstrations, and computer-

evaluated missions are selected by this method; each of these three programs has a dedicated thumbwheel and an "enter" switch. Other uses for thumbwheels could include entering tactics mission files, radio facilities sets, airfield data sets, etc. Thumbwheels are not appropriate when speed in entering numbers is important.

Light Pen. A light pen is an input device used to designate symbols or locations on a graphic CRT for certain programming operations. The following are typical uses for a light pen: erasing aircraft tracks to reduce clutter, activating or deactivating emitters, turning off radio facilities, activating or clearing malfunctions from a predetermined list, and initiating threat profiles or programs from a pre-established file.

Some light pens have an optional enhancement feature which causes the symbol being designated to brighten, identifying to the instructor the precise location illuminated. The instructor then completes the operation by a switch action, usually accomplished by pressing the point of the pen against the face of the CRT. Because of its diameter, the end of the light pen tends to obscure the symbol being designated, and the enhancement feature is needed to reduce errors. If an instructor station has multiple CRT's, each must be provided with a light pen to insure that the enhancement feature is uniformly available. A light pen is a very useful tool and simplifies many instructor operations. Using a keyboard to erase aircraft tracks, for example, would be cumbersome and time-consuming.

Some specifications, particularly those published by the Air Force, require that if a contractor proposes to provide a light pen, he must have back-up methods for accomplishing all the functions involved. The basis for

this restriction is believed to be a lack of confidence in the reliability of light pens and/or an appreciation of the ease with which light pens can be pilfered.

Track Ball. A track ball, which positions a cursor over the face of the CRT, performs essentially the same function as a light pen. It normally does not have an enhancement feature; but since the position of the cursor can be easily seen, enhancement of the designated location is not considered to be needed.

Other forms of cursor control are available. A joystick, which is sold by a number of vendors, accomplishes the identical function as a track ball. Edit keys, which are contained on a matrix that is part of the alphanumeric keyboard provided by some vendors, are also used to position a cursor, after which the programming actions can be accomplished.

Among the advantages of a track ball or equivalent device is the visibility of a cursor, as well as the fact that a track ball is not easily removed. On the other hand, a track ball requires more manipulation of controls than a light pen. In summary, it is concluded that either would be equally suitable for the AAHT.

Paging Keys. Paging keys are used to rapidly increment or decrement CRT pages. Paging keys can be made from spring-loaded toggle switches or similar three-position switches. In Device 2F119, two adjacent keys, the LINE FEED and DEL keys, on the alphanumeric keyboard are used for paging. Depressing one key increments the pages; the other key decrements.

Paging keys are useful when a number of related CRT pages must be called up sequentially. In Device 2F108, for example, the pages containing the checklists for the interior inspection, engine start, post-start, taxi,

pre-takeoff, and takeoff procedure can be called up with a paging key on the alphanumeric keyboard. This operation is considerably faster than entering the various page numbers in the conventional manner.

For the AAHT a paging key would be needed to generate sub-displays after a basic display has been called up via the function keyboard, as recommended previously. Since a small alphanumeric matrix is recommended, the paging key should be a spring-loaded toggle switch or similar control.

Programs

An increasingly important element of any instructional system is the group of programs which are designed to assist the instructor in teaching, evaluating, and critiquing the student. Depending on the number and scope of the programs provided, they make up the instructional capability of the trainer, and make it a teaching tool rather than merely a device to simulate an aircraft. These programs enable the instructor to, for example, control training problems, manipulate malfunctions, play back maneuvers that contain student mistakes, demonstrate the correct way to perform maneuvers, and evaluate student performance. Variously, these programs use CRT displays, hard-copy printouts, and voice and environmental sound recordings. They can be operated automatically or manually. A great variety of such programs is available; those that are potentially applicable to the AAHT are discussed below.

Malfunction Control. Malfunctions are normally controlled through either a function keyboard or an alphanumeric keyboard (or numeric matrix). With a function keyboard, if each switch is used to activate a malfunction, the size of the keyboard becomes inconveniently large when many malfunctions are to be simulated. On the other

hand, the advantage of a function keyboard is that the title of each malfunction can be printed on the face of the switch, making it easy for the instructor to select any malfunction desired.

With an alphanumeric keyboard, each malfunction is activated by entering a discrete number, thus the instructor must usually use an index to determine the number for the malfunction desired. This disadvantage is believed to be more than compensated for by the ability of the alphanumeric keyboard to handle a large number of malfunctions. Device 2F119, for example, has a "library" of over 600 malfunctions, which includes approximately 200 circuit breakers which can be tripped by the instructor. The index requires 11 CRT pages. Clearly, this number of malfunctions cannot be handled by a function keyboard.

Some trainers use a hybrid system consisting of thumbwheels to enter a malfunction number and push-button switches to activate or clear the malfunction. This method appears to have no advantages at all.

Malfunctions are usually programmed for either immediate or future activation. If immediate, the activation occurs when an "enter" switch is depressed or a keyboard carriage return is operated. Future activation is usually programmed by entering a mission clock time into the computer. A number of entries can be made at once, usually at the beginning of a training exercise, and the different activations can be spaced throughout the mission in accordance with the planned events. The scheduled time of activation can be shown in various ways on the CRT displays. Activation of each malfunction occurs automatically when the programmed mission clock time is reached.

This method of programming future malfunctions is not suitable if it is necessary to control the time of activation precisely. For example, if the instructor intends for an engine failure to occur immediately after the start of a missed approach, the student can inadvertently circumvent the planned activation time by normal inability to adhere to exact airspeeds and turn rates during the different maneuvers preceding.

Means can be provided, of course, for the instructor to manually intervene and reschedule the programmed malfunction, but the need for him to do so can be distracting and can affect his other instructional responsibilities. A conditional malfunction program is a better solution.

A conditional malfunction program causes malfunctions to occur when significant criteria have been attained. The criteria can include flight conditions such as airspeed, altitude, and heading; engine conditions such as rpm; and control states such as retraction of the landing gear. Mission clock time can be included when appropriate. Both "and" and "or" logic can be used. When several simultaneous conditions are required to be in effect before activation can occur, the time can be controlled very accurately.

A conditional malfunction program should be able to be constructed by the instructor on line, i.e. either just before or during a training exercise. This requires a CRT page to be assigned for this purpose. The format should enable him to readily enter the conditions and assign logic symbols.

When a conditional malfunction program is required, the specification should define the maximum number of conditions to be used for any malfunction (usually 4 or 5),

the number and type of conditions to be available for use (approximately 10), and the maximum number of malfunctions to be programmed for a training exercise (20 is recommended).

The availability of a light pen provides the instructor an additional capability for malfunction insertion. In Device 2F119 any malfunction can be activated or cleared by illuminating its number or title, respectively, on the malfunction index. Also, malfunctions can be listed on an area common to all graphic displays, called the Common Area, and can be programmed with the light pen in the same way as on the malfunction index. This feature permits the instructor to prepare a consolidated "menu" of malfunctions, rather than having to call up and refer to a number of pages if the malfunction index is lengthy.

In conclusion, it is recommended for the AAHT that malfunctions be programmable for immediate activation by using the alphanumeric matrix with non-page-dependent formats, and for future activation either by entering a mission clock time or by using a conditional malfunction program. Also, it is recommended that a light pen be used to activate or clear malfunctions via the malfunction index or the Common Area.

Procedure Monitoring. An important training objective is to insure that aircrews adhere to established procedures, for both normal and emergency procedures. For this purpose, displays are often provided which contain procedure checklists, derived from authoritative publications such as Flight Manuals. Usually these displays indicate whether the student accomplished all the steps in the procedure and whether they were done in the correct sequence.

In Device 2F108 and 2F119, the steps in each checklist are preceded by a column of sequential numbers. As the student completes each step, a number is displayed

in a second column, showing the actual sequence of accomplishment. If the student omits a step or performs one in a wrong sequence, his error can be easily recognized. If the checklist contains a step that cannot be monitored by the computer, a dash is displayed in the second column rather than a number. Steps such as "remove oxygen mask" or "obtain visual check of landing gear" are in this category.

Sometimes it is desirable to determine the time required by a student to complete a procedure. A program to compute the elapsed time can be developed for this purpose. Such a program usually starts when the malfunction occurs and terminates when the last procedure is accomplished, unless the last procedure cannot be monitored by the computer or consumes an unusual length of time, such as "land at nearest airfield."

It is recommended that procedure monitoring be required for the AAHT and that the two-column approach be specified. Computation of elapsed time is also considered to be a desirable feature for the AAHT.

Dynamic Replay. A dynamic replay program consists of a continuous, automatic recording of the immediately previous events of a training exercise. The purpose is to enable the instructor to interrupt the exercise at any time if he observes the student make a significant mistake, immediately go back to a point preceding the mistake, and then play back the recording of the student's maneuver while pointing out the errors and discussing the correct procedure.

It is considered that dynamic replay can be a powerful instructional tool. With this method, the instructor can point out to the student his errors in an effective way that no other form of critiquing can equal. However, opinion on the value of this technique is not unanimous. At the meeting of the AIAA Working Group on Training Simulation, held at Binghamton, New York, 13-14 April 1977, some representatives from airlines users of simulators

stated that they preferred to refly a maneuver rather than spend time during a training exercise in replaying mistakes. On the other hand, a rebuttal from an Air Force representative pointed out that some maneuvers, such as in air-to-air combat, do not have an "approved solution" and that evaluation can be accomplished only by replay and analysis.

Dynamic replay, if it is provided, usually includes the movement of the flight controls, and the indications of all instruments and indicator lights in the cockpit, as well as all displays used or available at the instructor station. In some versions of dynamic replay, throttle movement is not included, although, in a helicopter trainer, movement of the collective control should always be included, it is believed. The movement of toggle switches and controls such as landing gear and flap levers (not applicable to the AAHT) is almost never replayed, because of the mechanical engineering problems that would be involved. Motion and aural simulation and voice transmissions are usually replayed.

In Sperry SECOR's experience, the period of time available for replay has varied from five minutes, in its A-4 H/N trainers, to 20 minutes, in the EA-6B trainer. The latter period seems excessive, but the recording capability is also used to develop 20-minute demonstrations. Based on observation of the employment of the A-4 H/N trainers, it is concluded that a two-minute replay capability would be sufficient for most needs, but it is believed that users will almost invariably want a five-minute capability.

Controlling the replay can be accomplished either with push-button switches or an alphanumeric keyboard. In the A-4 H/N trainers, five switches are available to enable the instructor to commence the replay at a one-, two-, three-, four-, or five-minute interval preceding. In the EA-6B trainer, replay is commenced by use of a push-button switch but the interval is selected by the instructor entering minutes and seconds via the alpha-

numeric keyboard.

It is recommended that a five-minute dynamic replay capability be provided for the AAHT and that it be controlled with the alphanumeric matrix. Hardware controls as used in the A-4H/N trainers are simpler but require space on the function keyboard that will be at a premium in the AAHT.

Critique Replay. Another form of replay, which is available in Device 2F119 (EA-6B trainer), is a recording of the instructor station displays encompassing an entire training exercise. In Device 2F119 this capability is called "critique replay," and as the title suggests, is to be used for post-exercise critique purposes. All possible displays are included, whether or not actually generated by the instructor during the exercise. Also included are all student and instructor voice transmissions.

In Device 2F119 the recording is automatic, and the replay is accomplished by a combination of switch and keyboard actions in a manner similar to dynamic replay. By entering the start time with the keyboard, the instructor can select any part of the exercise that he desires to replay. He can do this repeatedly, thus covering only those parts of major interest. In addition, he can operate the replay at X2 and X4 speeds, in addition to normal, thus expediting any portions desired. A limitation exists in the fact that after a portion of an exercise has been replayed once, the instructor cannot replay it again except by returning to the beginning of the entire critique replay program.

To be most useful, a critique replay program should be able to use a display system separate from the instruc-

tor station, such as in a briefing room. With such a capability, thorough critiques can be conducted without interfering with other instructor's and student's use of the trainer.

A critique replay program is not considered to be a requirement for the AAHT, in view of the anticipated availability of a display printout capability, which will provide an equivalent critique aid. Display printout is discussed subsequently.

Demonstrations. Demonstrations consist of recorded maneuvers intended to show the student the correct procedure or technique. In contrast with dynamic replay, which shows the student how he performed the maneuver, demonstrations show how an expert performs it.

Demonstrations can be made either by recording an instructor flying the maneuver or by recording a computer-generated flight which uses ideal parameters (airspeed, heading, etc.). The first method is preferred, because it will contain minor imperfections in flying technique that make the demonstration realistic and credible. The student can attempt to equal or improve on an instructor-generated performance, an impossible goal for a computer-flown maneuver.

During a demonstration the student is in the cockpit observing the instruments and lightly holding the controls. Usually a recorded narrative is available which explains the highlights of the maneuver, bringing out the lessons that the student is expected to learn. Alternatively, the instructor can be required to provide the narrative through the intercom system, but this method, while more economical, can result in uneven instruction.

Demonstrations should include motion and visual simulation (in trainers that have those capabilities), movement

of power and flight controls, simulation of instruments and indicator lights, malfunctions and corrective action, aural simulation, and radio transmissions. The same problems as in dynamic replay will exist regarding reproducing the movement of toggle-switches and landing gear and flap controls, although these difficulties will be reduced in helicopter trainers that do not have many secondary controls. The point can be made that training objectives can be met in many instances by less than complete simulation during demonstrations, but, as usual, user acceptance must be reckoned with.

Demonstrations should also include freeze, replay, and fly-out capabilities. With these features the instructor can stop the demonstration and discuss points of interest in greater detail, replay portions of the demonstration for additional emphasis, and allow the student to complete a maneuver after the demonstration has shown a part of it.

Device 2F119, which possesses a comprehensive demonstration program along the lines discussed above, has special demonstration displays. Required by the specification, these show horizontal and vertical projections of the aircraft flight path, and contain at the bottom of the display a list of the events that occur during the demonstration. All other normal displays are also available for the instructor's use.

Of some value but lesser importance is the capability to conduct part of a demonstration in slow time. This would be useful in a maneuver, such as an instrument takeoff in a helicopter, in which many actions take place in a short time span. Conducting the demonstration at half speed, for example, would allow the narrative, which would be at normal speed, to more easily keep up with the

flight events. An alternative approach would be to freeze the flight every ten seconds, for example, until the narrative covered all the points to be made.

Most users will want to be able to develop their own demonstrations, in addition to those initially delivered by a contractor. Furthermore, there will always be a need to update demonstrations as procedures change. Thus, demonstration programs should be designed to facilitate user preparation, editing, and testing.

During the preparation of a demonstration, one of the most difficult tasks is the coordination of the narrative with the flight events. Controls are needed that will permit the preparer to narrate small portions of the script at a time, repeating those that have errors until the entire script is finally assembled. The controls on Device 2B33 entitled RECORD MANEUVER MARK, FREEZE ON MANEUVER MARK, and EDIT PAUSE are examples of a satisfactory solution to this problem.

It is considered that the AAHT should have a program of demonstrations as described above, except for the special demonstration displays. Recorded narrative; full simulation except for movement of secondary controls; freeze, replay, and fly-out; slow time as well as normal; and controls for user preparation and editing of demonstrations should be required by the specification. The special demonstration displays are considered to be in the "nice-to-have" category, not required because of the availability of other displays. A capability to store on disk approximately 200 minutes of demonstration, to be divided into up to 20 individual demonstrations as the user desires, is recommended.

Display Printout. A useful aid for critique purposes is the ability to reproduce significant CRT displays. With

this capability, an instructor can print out, for example, map displays that reveal how a student accomplished a maneuver such as flying a TACAN arc, or alphanumeric displays that contain instrument readings at a critical time in a maneuver such as initiating a missed approach. In some respects, display printout is a duplication of critique replay, if the latter is also available. The advantage of display printout, however, is that it provides a permanent record.

Device 2F119 uses a Versatec printer-plotter to obtain display printouts. This system requires approximately 15 seconds to make a print. Normally, in Device 2F119, the instructor stores all displays of possible interest during a training exercise, then reviews them after the exercise is completed, and finally prints only the ones that he decides to use during the critique. For these functions, the trainer has three momentary-action pushbutton switches labeled CRT STORE, PREVIEW, and PRINT. Another switch, labeled REJECT, enables the instructor to reject displays that he does not want printed. A total of 100 displays can be stored, 50 by the flight instructor and 50 by the tactics (EW) instructor. Since the map displays in Device 2F119 contain a lengthy depiction of the aircraft track, in the form of a dotted line that, under some circumstances, can show over an hour of flight history, the display printout system can be used to record the entire training exercise.

It would be desirable to allow the instructor to print a display immediately if he wishes, without storing a previewing it. This capability would be expensive, however. Two approaches are possible: a software approach that would require substantial memory, or a hardware approach using a Sanders system (the Model 570 Graphic Hard Copy Unit) for reproducing CRT displays, which would

cost approximately $20,000 per system. The Sanders system is not as versatile as the Versatec, hence the latter would still be needed. The cost of immediate printouts would therefore be additive to the 2F119 approach.

The need for immediate printouts should be weighed against these costs. It is considered that the occasions for their use would be infrequent; and, furthermore the instructor would have to accomodate a 30-second interval for every printout, during which he could not print any other display that he might also want. In view of these considerations, it is recommended that for the AAHT only the approach used in Device 2F119 be provided.

Performance Evaluation. Observing and evaluating student performance is one of the most important functions of an instructor, along with initiating and controlling the training exercises. Many aspects of performance evaluation, particularly those that involve obtaining numerical results, are amenable to computer operation. Assistance of this nature from the computer, when available, enables the instructor to devote more attention to those other aspects that require subjective judgment.

A certain amount of controversy exists regarding the dividing line between "objective" measurement that the computer can make and subjective evaluation that only the instructor can perform. There can be no doubt about the ability of computer programs to measure and record miss distances in weapon delivery, for example; but a question sometimes arises regarding the computer assigning evaluations of "satisfactory" or "unsatisfactory" to such scores, even though the criteria are established by human judgment and are able to be changed by merely modifying the computer program. More controversial is the ability of the

computer to evaluate, in an instrument approach, for example, a student's inability to maintain a prescribed airspeed compared with his failure to remain above the minimum descent altitude. Different parameters can be weighted in the computer program, but there is some reluctance to attempt to assign values to those that are as unlike as the example cited above.

Phases of training that most easily lend themselves to computer evaluation are instrument flight and weapon delivery. Visual flight is also feasible, but only if techniques of evaluating instrument flight are used. Least suitable, for the AAHT, are such phases as target acquisition and identification, response to hostile threats, and communications.

For instrument flight, the technique usually used is to divide a maneuver into segments which contain a number of variables (airspeed, altitude, heading, etc.) that can be evaluated simultaneously. Each variable is assigned a reference value according to the requirements of the maneuver (an altitude of 1000 feet, for example) and a tolerance ($\pm$ 100 feet, for example) which the computer uses to determine whether the student's performance is within standards.

At the end of the training exercise the computer can report overall results in a number of ways. The usual method is to summarize for each parameter the cumulative time out of tolerance and the total number of deviations. In addition, the cumulative time out of tolerance can be divided by the cumulative time of monitoring, resulting in a percentage that can represent a "score" for each parameter.

There are two possible approaches to the design of performance evaluation programs for instrument flight.

These can be entitled "fully automated" and "instructor operated." They are illustrated by Sperry SECOR's EA-6B and A-4H/N trainers, respectively.

In the fully automated program the computer performs all operations, including determining when to start and stop monitoring each parameter, and when to advance from one segment to the next. This method is least demanding on the instructor during an exercise, but has the disadvantage of inflexibility.

Programming an entire training exercise to be monitored via the fully automated approach requires considerable effort, not only in coding the program but also in planning the flight profile, defining the segments, and establishing the reference values and tolerances. Once programmed, an exercise is not readily changed. This inflexibility is recognized in Device 2B33 by the requirement that major segments of the visual and weapon delivery checkrides, which are part of the performance measuring programs, be useable as "automated training exercises."

Fully automated programs are susceptible to anomalies that occur when the student makes mistakes that the program has not anticipated. In this case the computer either advances to the next segment prematurely or fails to advance at all. The result will be that the student is on one segment of a maneuver and the computer is monitoring the parameters of a completely different segment, usually an adjacent one. Consequently, the student will be charged with deviations that are not deserved and not charged with true deviations.

To correct for this problem, Device 2F119 uses two momentary action push-button switches, labeled MANUAL ADVANCE and MANUAL RETRACT, to enable the instructor to realign the performance evaluation program with the

student's flight profile.

In the instructor-operated program, the instructor makes the decision when to start and stop monitoring. In fact, in the A-4H/N trainers, the program is designed so that the instructor makes all program entries manually, using the computer only for measuring and recording. Employing a special CRT page, the instructor enters with the alphanumeric keyboard all reference values and tolerances into a column entitled STANDBY. At the proper time in a maneuver, he instructs the computer to start monitoring, and the values then transfer to another column entitled RECORDING. Throughout the exercise, the instructor keeps one segment ahead of the student, entering values for the next segment while the computer is monitoring and measuring those previously entered.

This approach has the advantage of complete flexibility. Normally the instructor will pre-plan all of his entries so that his decisions will only be concerned with starting and stopping the computer monitor function, but he will have the capability to "ad lib" at any time by adding or omitting parameters and modifying tolerances.

On the other hand, this approach has the disadvantage of imposing rather severe demands on the instructor. Only the fact that Sperry SECOR's A-4 series of trainers has a device operator as well as an instructor makes it practical for extensive use. Even with both an instructor and device operator available, it is considered that a maximum of three parameters can be monitored simultaneously during each segment in a normal maneuver.

For the AAHT it is recommended that both fully automated and instructor-operated programs be provided. This approach provides all of the advantages of each - specifically the "capacity" of the fully automated program and

the flexibility of the instructor-operated program. The instructor can use the fully automated method on preplanned missions such as checkrides, and the instructor-operated method for individual maneuvers or short exercises.

Evaluation of weapon delivery usually concentrates on measuring the miss distance rather than monitoring flight parameters. To some degree the two can be combined: dive angle, airspeed, yaw, acceleration, entry altitude, pull-out altitude, etc. can be evaluated during weapon delivery maneuvers in the same way as during instrument flight, if the criteria for satisfactory performance can be determined. However, the result of improper procedures will usually be an unsatisfactory miss distance, hence it seems to be adequate to evaluate only the latter.

For the AAHT, the normal weapon delivery maneuver will consist of a stable hover behind or emerging from some type of concealment, and the parameters that could logically be evaluated are limited. The time to acquire the target and launch a weapon could be one. Otherwise, it is concluded that only accuracy measurements need be computed, i.e., miss distance and relative location of impact.

On Device 2B33 the weapon delivery display contains read-outs for altitude, airspeed, heading, and other flight parameters. These will be useful if display printouts are made of this page during weapon delivery, and a similar approach should be followed for the AAHT.

Displays

Displays serve a number of purposes in a trainer's instructional system. First, they are the means by which the instructor observes the altitude, location, and performance of the simulated aircraft, and monitors the

progress of the student through training exercises or problems. Second, displays can contain reference data, such as an index of pages or lists of malfunctions or emergency procedures. This type of information can be contained elsewhere, such as in instructor handbooks, but having it available on the CRT is more convenient for the instructor. Finally, displays are often part of the process by which the instructor accesses the computer. Device 2F108, with its relative, few hardware controls and its page-dependent CRT formats, is an example of this function.

Considering the above purposes, one can define the use of displays as being either informational or instructive. Combinations of these uses are possible on any single display page, although in Device 2F108 this practice is minimized and purely informational displays are called "monitor" pages.

Another way of classifying displays is by format. From this viewpoint, displays can be categorized as either graphic or tabular. Most graphic displays are map-like and are generated by a program that draws vectors and curves and records the aircraft position and track. Another form of graphic display depicts aircraft instruments, and is usually called psuedo-instrument display. Tabular displays contain tables or lists of alphanumeric data. Combinations of these formats are frequently used.

Repeater instruments are a form of display. They have the advantage of being easy for the instructor to interpret, and the disadvantages, compared with psuedo-instrument displays, of greater cost and less reliability. Repeater instruments are usually not provided when the instructor station is located in or beside the cockpit and the instructor can observe the aircraft instruments directly.

Graphic Displays. Map displays, the most common form of graphic displays, can be classified into four types: cross-country, combat situation, terminal area, and GCA/ILS. Some combinations are possible, but the general practice is to keep them separate.

Cross-country displays usually depict the radio navigation aids (TACAN's, VOR's, and non-directional beacons) located in a commonly-used training area such as the vicinity of Fort Rucker, Alabama. Sometimes symbols representing airfields, obstructions, and elevations, and lines to indicate airways are included. Inasmuch as instrument navigation will be a capability of the Advanced Attack Helicopter, the AAHT should have a cross-country display for such training.

Since AAHT's will be procured for field use, it is recommended that the instrument training gaming area and cross-country displays be designed to represent the area in which the trainer site is located. For example, Fort Hood-based trainers should have a cross-country display oriented around that area of Texas; and the Fort Knox-based trainers' display should depict Kentucky and surrounding states.

Combat situation displays, often provided for trainers with an electronic warfare mission, usually depict hypothetical combat areas not identified with a specific locality, although geographic accuracy would be easily possible and might enhance training. Normally, the instructor is able to program threats at various locations and control their responses to ownship actions.

Combat situation displays are not expected to be provided when the trainer has a visual system, since the instructor can see the geographic features and threat locations directly. However, it is considered that a combat situation display consisting of a map of the visual

system area would assist the instructor in monitoring the progress of training exercises. Such a display should have surface topographical and cultural features defined with contour lines and appropriate symbols, should depict the aircraft track with a continuous or interrupted line, and should show the location of targets and threats with symbols and descriptive legends. The display combat situation could be used by the instructor to program threats on the visual display and otherwise control the problem situation.

Terminal area displays, using a scale considerably larger than for cross-country displays, depict the area surrounding an airfield, or group of airfields, and contain symbols for the airfields and the radio aids associated with the various approaches. Data on airfield elevation and radio frequencies available are usually included. In Device 2F119 (EA-6B Trainer) there are approximately 120 terminal display pages depicting the principal Navy, Marine Corps, and Air Force airfields in the United States.

A special category of terminal area displays is approach departure displays. These displays depict published instrument approach and departure patterns on which the track of the aircraft is superimposed as the student performs the prescribed procedures. The displays contain symbols for radio aids, marker beacons, obstructions, ILS localizer courses, and holding patterns, and show all appropriate course lines with magnetic headings. These displays are very useful to the instructor in monitoring that phase of instrument training.

Sperry SECOR's B-52 trainers display all published approach and departure patterns for Castle, March, and Beale Air Force Bases, which are contained in the gaming area for those trainers. Each pattern is depicted on a

separate CRT page; there are 19 such pages in total. For larger gaming areas involving a greater number of bases, some selectivity should be exercised. For Device 2F119 Sperry SECOR has proposed to provide 15 displays for bases to be determined, with storage for 35 additional which the users, at NAS Whidbey Island, will program themselves.

It is considered that approach/departure displays should be designed to meet the instrument training needs of the local user, in the same manner as recommended in cross-country displays.

GCA/ILS displays normally contain a vertical projection of the final approach course and a horizontal projection of the glide slope. Aircraft symbols and tracks are shown on both projections. Usually the scale of the glide slope angle is exaggerated, i.e., a 3-degree glide slope is shown as approximately 15 degrees. The angle is normally fixed, regardless of whether a different glide slope, such as 2.5 degrees, is required. If the aircraft has ILS, both ILS and GCA approaches can be monitored with the same display. In Device 2F108, 2F119, and Sperry SECOR's B-52 trainers, the GCA displays contain a text providing standard GCA instructions so that the instructor need only read them verbatim to the student. These instructions change every few seconds, as required by the student's flight path.

It is recommended that the AAHT be provided a GCA/ILS display similar to that described above. If the aircraft has ILS, the instructor will be able to observe the student's instrument during ILS approaches or can use the GCA/ILS display.

It is possible to provide an automatic voice recording

of all GCA instructions, thus relieving the instructor of having to read those on the CRT display. Such a system either would require a separate recorder, an expensive approach; or could use the recorder capability dedicated to dynamic replay, which would prevent it being used for the latter function. In view of these undesirable aspects, such a capability is not recommended.

Tabular Displays. Tabular displays comprise those displays containing only alphanumeric data rather than graphic depictions. They can serve any of the purposes outlined previously - student monitoring, information storage or computer interaction. The programs recommended for the AAHT will require certain tabular displays; other displays are dictated by the normal requirements of trainer operation. The following tabular displays are considered to be necessary or highly desirable:

Initial Conditions. Defines the flight and environmental conditions for the commencement of a training exercise. Ten sets (each set to be displayed on a CRT page) are recommended.

Malfunctions. Lists all programmable malfunctions. Assigns each a number to be used in the input format.

Conditional Malfunction Programming. Provides a format for the instructor to use in constructing a conditional malfunction program, and in modifying one that has been constructed earlier.

Procedure Monitoring. Lists the sequential steps for each normal and emergency procedure. The appropriate procedure can be automatically displayed when a malfunction occurs, a feature that is recommended for the AAHT (a manual override to inhibit the automatic feature is also recommended).

Procedure Index. Lists all procedure monitoring displays. Used by the instructor to manually generate a display.

Performance Evaluation (Automated). Displays the current segment for an automated performance evaluation program and shows the parameters being monitored with their reference values and tolerances. The previous and next segments can be included. Also, any out-of-tolerance values resulting from student errors can be reported via this display.

Performance Evaluation (Instructor-Operated). Provides a format to be used with an instructor-operated performance evaluation program. Permits the instructor to manually enter and store reference values and tolerances and to start and stop recording at will. Can display out-of-tolerance values.

Weapon Delivery. Provides results of weapon delivery, i.e., rounds fired and rockets/missiles launched, hits, miss distances and impact points or areas. Can include existing station loading, positions of cockpit select switches, and aircraft flight data that would assist instructor in evaluating weapon delivery.

In addition to the displays listed above, a page is needed for programming in-flight changes in aircraft status and configuration and environmental conditions. Parameters such as aircraft latitude/longitude, altitude, heading, airspeed, fuel quantity, internal stores, wind direction and velocity, barometric pressure, etc. would be listed on the page and would be able to be modified at any time by the instructor making keyboard entries as described previously for Device 2F108. Visual system functions could also be controlled by the same method.

This approach was used by Sperry SECOR in its B-52 trainers. A CRT display entitled the MONITOR/CONTROL page contains approximately 35 informational and 70 programmable items. It is the only page used for interaction with the computer; all other pages are for monitor functions.

With respect to the AAHT, it is considered that the method used to perform on-line programming should be discretionary with offerors and that the specification should not require a monitor/control page. Sperry SECOR, however, prefers this approach.

Common Displays. Many displays contain an area in which flight status and other information of frequent interest to the instructor are continually shown. In Sperry-SECOR's B-52 trainers this is called the Reserved Area; in Device 2F119 it is called the Common Area. In both trainers it is only contained on the graphic displays. In Device 2F108, this area is called the Status and Indications Display, and is contained on most of the tabular displays (there are no graphic displays). A similar area is contained on displays of Device 2B31 and 2B33.

It is recommended that the specification for the AAHT stipulate that a common area be provided on all graphic displays and that it contain the following information:

Flight Status. Indicated airspeed, baro altitude, magnetic heading, vertical speed, rotor rpm, torque, fuel remaining, and wind direction and velocity. This data should be up-dated every second.

Malfunction Status. Number and abbreviated title of all existing (activated) malfunctions.

Communications Status. Frequencies of all tuned-in

and operating equipment. SIF code selected if the AAH is so equipped.

Switch Status. A list of the last six switch actions taken by the pilot or CPG.

The common area displays in Device 2B31 and 2B33 contain a plot of altitude and airspeed for the preceding 12-minute period. It is considered that this feature is of marginal value and is not recommended to be specified in the AAHT.

Summary

The foregoing discussion of instructional system controls, programs, and displays is summarized in Tables 25, 26 and 27.

Instructor Station Configuration

Once the controls, programs and displays are specified, the configuration of the instructor station remains to be defined. The first requirement is to specify the number and size of the CRT's. It is considered that the same philosophy should apply in this case as to instructor station controls, i.e., the specification should be as explicit as possible, to insure that the user receives a desired level of performance.

It is believed that the functions contemplated for the AAHT and the displays recommended will require providing three 21-inch CRT's at the instructor station. During instrument flight training, the instructor will usually use one of the map displays, the monitor/control page, and either the performance evaluation display or the pseudo-instruments display. During training in emergency procedures, the malfunction display, the procedures monitoring display, and either the monitor/control page or the pseudo-instruments display. During training using the visual system, the instructor will probably want the combat situation display, the monitor/control display, and the weapon delivery display. The instructor will be able to monitor flight status by keeping in view a graphic

Table 25. Instructional System Controls

EQUIPMENT	APPLICATION TO AAHT	TO BE SPECIFIED
Alphanumeric Keyboard	Possible input device	No
Function Keyboard	Contains hardware controls	Yes
Numeric Matrix	Additional input device	No
Alphanumeric Matrix	Substitute for alphanumeric keyboard	No
Thumbwheel	Possible input device	No
Light Pen	Possible input device	Yes
Track Ball	Substitute for light pen	No
Paging Key	Rapid access of display pages	Yes

Table 26. Instructional System Programs

PROGRAM	APPLICATION TO AAHT	TO BE SPECIFIED
Immediate Malfunctions	Initiates malfunctions on instructor demand.	Yes
Future Malfunctions	Uses mission clock to program malfunctions for future occurrence.	Yes
Conditional Malfunction	Uses algorithms to cause automatic initiation of malfunctions. Reduces demands on instructor.	Yes
Procedure Monitoring	Evaluates student adherence to published emergency and normal procedures.	Yes
Dynamic Replay	Replays trainer activity and instructor station displays for immediate use.	Yes
Critique Replay	Selectively replays instructor station displays during entire exercise. For post-exercise critiques.	No
Demonstrations	Replays correctly-performed maneuvers for student to observe.	Yes
Display Printout	Prints CRT displays selected by instructor.	Yes
Performance Evaluation		
Instrument Flight	Using predetermined standards, evaluates student performance along segments of a pre-planned instrument flight profile.	Yes
Visual Flight	Evaluates student performance along segments of a pre-planned visual flight profile.	No
Target Acquisition	Not feasible.	No

Table 26 (Cont.)

PROGRAM	APPLICATION TO AAHT	TO BE SPECIFIED
Weapon Delivery	Determines impact points and miss distances	Yes
Response to Hostile Threats	Not feasible	No
Communications	Not feasible.	No

Table 27. Instructional System Displays

DISPLAY	APPLICATION TO AAHT	TO BE SPECIFIED
Cross-Country	Depicts instrument training area	Yes
Terminal Area	Depicts area around airfields	Yes
GCA/ILS	Depicts final approach course and glide slope	Yes
Combat Situation	Depicts combat training area	Yes
Approach/Departure	Depicts Standard Instrument Departures (SIDs) and published approaches	Yes
Initial Conditions	Defines initial flight and environmental conditions	Yes
Malfunctions	Lists all programmable malfunctions	Yes
Conditional Malfunction Programming	Provide format for conditional malfunction programming.	Yes
Procedure Monitoring	Lists steps in each normal and emergency procedure	Yes
Procedure Index	Lists all procedure monitoring displays	Yes

Table 27 (Cont.)

DISPLAY	APPLICATION TO AAHT	TO BE SPECIFIED
Performance Evaluation (Automated)	Displays segments of automated performance evaluation program	Yes
Performance Evaluation (Instructor Operated)	Provides format for instructor - operated performance evaluation program	Yes
Weapon Delivery	Provides weapon delivery results	Yes
Monitor/Control	Provides a vehicle for on-line parameter changes	No
Common Area	Provides flight status information on all displays	Yes

display which will always have a common area display. Thus in many training situations the instructor will want to keep on one of the CRT's graphic display such as the cross-country page in order to keep a common area in view.

In order to monitor the pilot and copilot/gunner visionic displays, the instructor will need two dedicated CRT's. Five-inch CRT's are recommended. As each crewman selects a TADS, PNVS, or IHADSS display, the CGI image that he sees on his cockpit displays will be reproduced on the instructor station CRT's.

In addition, five 7-inch CRT's will be needed to enable the instructor to monitor the visual scene. These should be arranged horizontally, probably along the top of the instructor's console.

In view of the fact that the common area can contain readouts of all flight and engine instruments, a repeater instrument panel or a pseudo-instrument display is not considered necessary. However, the exclusive use of alphanumerics for instrument readings requires considerable user acceptance, and a pseudo-instrument display is recommended for the AAHT.

The specification should require that MIL-STD-1472A be adhered to in the design of the instructor station, with particular reference to a 15-degree downward line of sight. This requirement is intended to provide for instructor comfort, and results in the 21-inch CRT's being mounted with the longer dimension horizontal.

Some ingenuity will be required in designing displays and arranging the controls and input devices. Unfortunately, in the past, too little attention has been to the needs of the instructor. Both efficiency and comfort can be achieved if the effort is made.

An artist's concept of the instructor station is depicted in Figure 46.

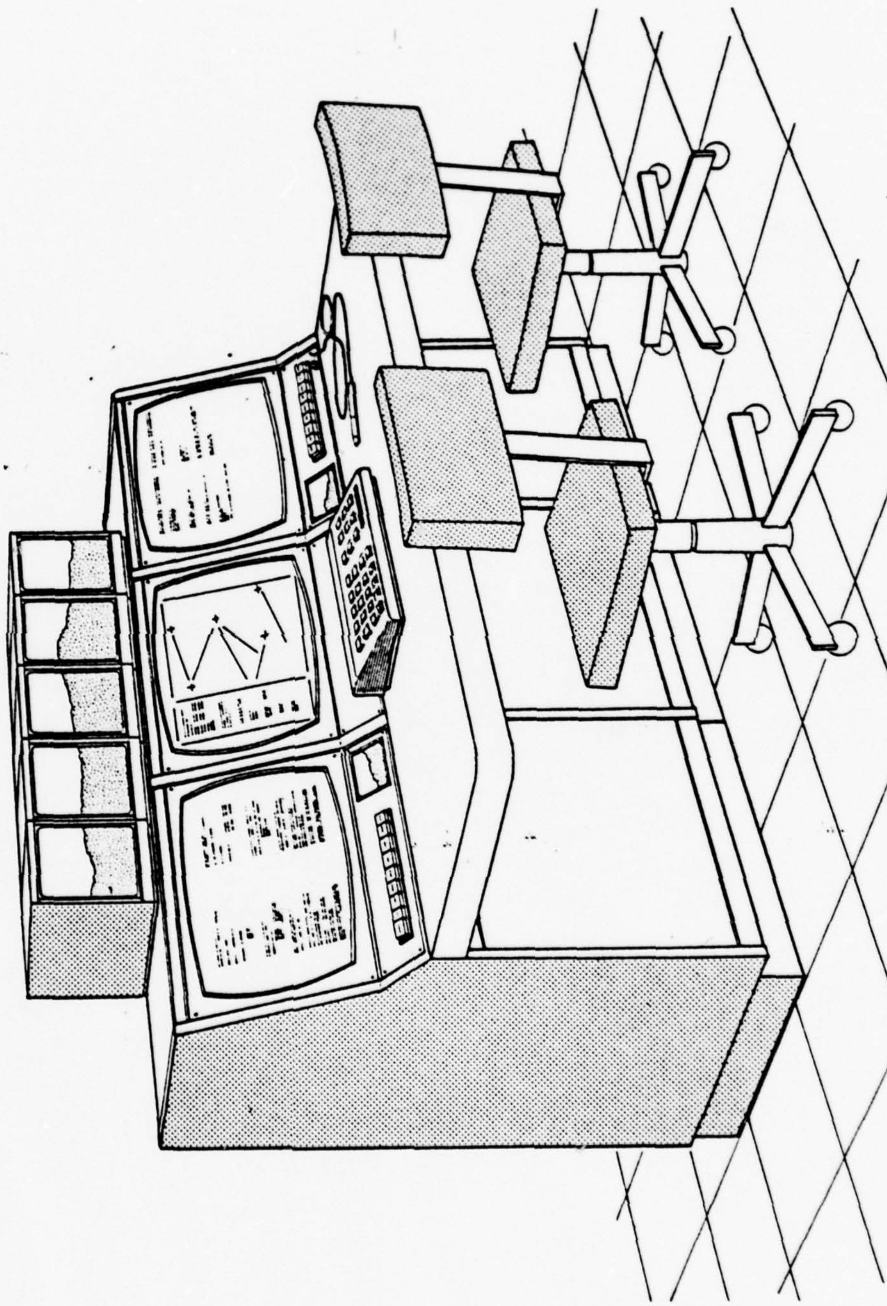


Figure 46. Instructor Station Configuration

SECTION VI

ACHIEVEMENT OF CONCEPT FORMULATION OBJECTIVES

The study has attempted to achieve the six AR 71-1 concept formulation objectives which are listed in the NTEC "Study Outline for AH-63/64 Flight and Weapons Simulator Concept Formulation". The following is a discussion of the extent to which each of the objectives has been attained.

Objective 1. Primarily, engineering rather than experimental effort is required and the technology needed is sufficiently in hand.

In general, this objective has been met. In some cases, innovative approaches have been recommended but they have in every instance been within current technology. Presented below is a brief summary analysis of the complexity of engineering effort and the degree of risk anticipated with respect to each trainer system or support area.

Cockpit Module. The recommended trainer cockpit is a conventional replica of the helicopter cockpit. Tandem seating, as in the helicopter, is proposed. An aluminum frame with removable skin panels for maintenance access is recommended. Ingress and egress would be accomplished over the cockpit sill, as in the helicopter. The cockpit ventilation system would consist of a commercially available air conditioning unit operating through diffusers replicating those in the helicopter. The technological risk in these concepts is considered to be nil.

Flight and engine instruments are proposed to be either operational equipment or synthetic. Flight and engine controls are recommended to be operational equipment. The control loading system would consist of electrohydraulic force actuators in combination with bungee springs. Again, these concepts are conventional and commonly used and contain no significant technological risk.

Visionic equipment would be simulated by using CGI techniques to project images of daylight scenes, targets, and IR scenes for the TADS, PNVS, IHADSS, and direct view displays, both in the cockpit and at the instructor station. Magnification, as selected by the pilot and CPG, would be achieved by recomputing the images. The risk in this approach is considered to be low, although the images would be subject to the usual problems of detail and resolution currently inherent in all non-cinematic visual systems.

Target designation systems, i.e., laser, would be simulated by computational methods rather than visual. The position and flight parameters of the helicopter and the preprogrammed position of the target would be computed, and valid designations and probable hits, based on ballistic data for the Hellfire missile, would be determined. Both direct and indirect modes of fire would be simulated in the same way. The risk in this area of simulation (target designation systems) is considered to be low.

Motion System Module. A six-degree-of-freedom motion system with reduced excursions is recommended, with a commercially available hydraulic power supply. All elements of the contemplated motion system are considered to be conventional and to involve no technological risks (integration problems are discussed under visual systems, below). The reduced excursions, required in order to preserve a maximum downward field of view, as well as not to obstruct the visual system projectors, will provide adequate onset cues when used in conjunction with electronically maneuvering the visual scene.

Visual Systems Module. For "full mission" training, a CGI visual system is proposed. The recommended display system uses a wide-angle (180-degree), fixed base, cylindrical screen and five Hughes liquid crystal light valve projectors.

The selection of CGI is considered to be a low risk decision, in view of the fact that a cinematic system is also

proposed for part-time training in areas that require the highest degree of scene detail, depth of field, and resolution. Using current technology, CGI will provide satisfactory scene detail for training in aircraft handling, normal and emergency procedures, terrain flight, weapon employment, tactical decision-making, and crew coordination. Particularly noteworthy is the ability of CGI to depict enemy threats dynamically, and to reproduce air-to-ground weapon effects (tracers, missile plume, flash and smoke from detonations, etc.).

Current technology is considered to be capable of generating a scene with up to 8000 edges. Technology in the next one to three years is expected to be able to generate a scene with 16,000 edges, which would improve the realism and acceptability of CGI scenes. However, the training objectives for the full mission trainer will be able to be met without dependence on future technology.

The selected display system is also considered to involve low risk. The fixed-base, cylindrical screen, which would be located 28.6 feet from the cockpit, would permit both the pilot and CPG to see the same display with acceptable parallax (varying from zero to a maximum of 5.7 degrees). It would thus obviate any need for separate cockpits and separate display systems, would enable accurate replication of the helicopter cockpit, and will enhance training involving crew coordination. The projectors would be located only 6 degrees below the centerline of the screen, and the angle subtended by the projected image, 73° in the vertical plane, is certainly within the capability of lens manufacturers.

The Hughes liquid crystal light valve projector is considered to be a medium risk selection. However, the GE light valve and Eidophor projectors are lower risk alternatives to the Hughes system. It is anticipated that the Hughes system, with color, will be available in 1978, early enough for evaluation and a decision to use an alternative system should that be

necessary. Significant advantages of the Hughes projector make it worth the added risk.

The problem of integrating motion and visual systems is well-known, and solutions through the use of extrapolation algorithms are available. The use of a fixed screen rather than a display system mounted on the motion base somewhat complicates the integration problem because an additional computation and correction of the visual scene will be required during the washout motion. However, it is considered that solutions to the basic integration problem will be applicable to the recommended configuration.

For part-task training, which will include terrain navigation target detection and identification, and weapon employment, a cinematic visual system is proposed. The technology in film cameras and projectors is mature and highly developed, resolution approaching one minute can be obtained, and this method of non-interactive training is thoroughly proven. Synchronization of CGI visionic displays with cinematic scenes, as proposed, is innovative but technologically involves no significant risk.

Instructor/Operator Module

The recommended instructor/operator module would consist of a three-CRT, two-position instructor station located remotely from the cockpit. This concept, in contrast to an on-board instructor station, provides maximum opportunity for development of instructional capabilities, permits the use of more than one instructor during integrated (pilot and CPG) training, and allows observers and supervisors to observe training exercises. This approach contemplates the use of a number of additional small CRT's to monitor the cockpit visionic displays and the general visual scene; however, any configuration would require monitor CRT's for visionic displays. Instructional systems contemplated would include a variety of controls and indicators, CRT displays, and training programs, all of which are conventional in concept and design. In summary, the proposed instructor station is considered to involve very low risk.

Computer System Module. The study addresses the items listed in the Computer Section Study Outline contained in Attachment 4 to the contract. Recommended are: the use of FORTRAN for the simulator software; the use of assembly language for the real-time executive program, the graphic page compiler, and the off-line test program; the use of a contractor-developed real-time executive rather than a vendor-supplied Operating System, if the contractor is already familiar with the computer; the use of on-line diagnostics if they can be purchased from the vendor; and the use of MOS memories when available. In the survey of 32-bit minicomputers, the SEL 32/75 is recommended. These recommendations are all considered to involve low risk.

Interface System. The study recommends that a contractor-designed interface system be used rather than a commercially available one. This is a low risk recommendation if the contractor has experience in designing interface systems.

Reliability and Maintainability. The study predicts an MTBF of 92 hours and an MTTR of .54 hours. Inherent availability would be .9942. These estimates are considered to be low risk.

Integrated Logistics Support. The study recommends that conventional ILS concepts be followed.

Device Power and Air Conditioning. The study concludes that the configuration recommended will cause no unusual requirements for device power and air conditioning.

Facility Considerations. The principal facility considerations derived from the concepts contained in the study are that the trainer building must have a bay with a ceiling approximately 35 feet high, to accommodate the 31-foot screen, and that the interior of the bay be painted with black non-reflecting paint. There are no significant risks attached to the facility considerations.

Objective 2. The mission and performance characteristics are defined.

This objective has been met in various sections of the report. The following is a summary of the conclusions of the report with respect to this objective, discussed according to the operating characteristics listed in paragraph 3.1.2 of the NTEC "Study Outline".

Record and Playback. "Dynamic replay" and "critique replay", which are forms of record and playback, are discussed in the Instructional Systems part of Chapter V, and a five-minute dynamic replay capability for the AH-64 FWS is recommended.

Performance Evaluation. Various methods of performance evaluation are discussed under Instructional Systems. Recommended are both "fully automated" and "instructor-operated" programs for evaluation of instrument flight, and weapon delivery evaluation programs for determining impact points and miss distances.

Flight Dynamics. This subject is discussed in detail in Chapter V, and three approaches -- the modified blade element approach, the coefficient approach, and the Sperry SECOR specific response approach -- are analyzed. The conclusion is made that any of these approaches can lead to an aerodynamic model within the accuracy requirements of the AH-64 FWS.

Automatic Self-Check. The study recommends that a highly-automated daily readiness check be developed. The check would consist of a series of modules designed to test various trainer systems (I/O, CRT displays, instruments, visual system, etc.) and would be conducted by one person, first at the instructor station and then in the cockpit. It would be able to be completed in approximately fifteen minutes. Using the keyboard at the instructor station and a Digital Readout Unit in the cockpit, the instructor would be able to initiate successive steps in the check and obtain readouts to use in monitoring and controlling the program.

Navigation. The navigation equipment of the AH-64 -- ADF, HARS, and Doppler -- is relatively simple, and the study recommends that it be simulated by conventional approaches.

Communication. The communication equipment of the AH-64 consists of UHF, VHF-AM, VHF-FM, and security systems. The study recommends that it be simulated conventionally. Line of sight calculations would be performed by the visual system computer. The security equipment would be simulated both for the purpose of monitoring the students' use of the switches and for providing training in listening to and understanding the secure audio.

Training Problem Formulation and Presentation. Under Instructional Systems all proposed programs to initiate and control training exercises are discussed, and the CRT displays that would accompany these programs are described. Specific programs included are malfunction control, procedure monitoring, and performance evaluation. Displays include both graphic (cross-country, terminal area, GCA/ILS, approach/departure, and combat situation) and tabular (initial conditions, malfunctions, procedure monitoring, performance evaluation, weapon delivery, monitor/control, and common area). Adaptive training programs are not specifically recommended.

Demonstrations. Computer-controlled demonstrations are discussed and the recommendation is made that 200 minutes of demonstration be provided, to be divided into up to 20 individual demonstrations.

Automated Instructor Functions. Fully-automated performance evaluation programs are discussed, and the recommendation is made that they be provided, along with instructor-operated programs.

Approaches to Optimize Operation. Many approaches to assist instructors are presented. Among those recommended are a program (conditional malfunctions) to enter malfunctions automatically when certain pre-programmed conditions have been attained; a program to display standard GCA instructions on the GCA/ILS display; a combat situation display to assist instructors in programming threats; paging keys to enable the instructor to rapidly access CRT displays; a light pen or track ball to provide a means to enter data without typing alpha-numerics; and a common area display to provide frequently-needed status information.

Other. Other definitions of performance are contained in the discussions of the motion system, visual system and computer system.

Objective 3. A thorough trade-off analysis has been made.

A number of trade-off analyses were made during the study. Most of these involved accepting a reduced capability in one area in return for an increased capability in another, more important or more desired area. The following are some of the most significant of these trade-offs:

1. In the area of visual display systems, the study group accepted the problems of integrating the motion and visual systems in return for the advantages of a single, integrated cockpit with a fixed screen, not attached to the motion base. Mounting the screen on the motion base would have required either accepting a serious parallax problem with an integrated cockpit, or resorting to two cockpits and two display systems, which the study group intended to avoid if possible.

2. In choosing between CGI and model board visual generation systems, the study group accepted the stylized CGI scenes in order to obtain the greater flexibility and scope that CGI technology offers.

3. An unproven TV projection system, the Hughes liquid crystal light valve, was selected in order to obtain the increased reliability and lower maintenance and operating cost that it offers. In this case, however, two acceptable alternatives are available.

4. An adequate (180 degrees) but less than maximum horizontal field of view was accepted in order to limit the number of projectors to five.

5. The study group decided to reduce the range of motion system excursions in order to minimize the impact on the visual system. Using the maximum excursions possible with the selected motion system design would have required a larger, perhaps partitioned screen, and additional projectors.

6. In deciding to recommend a part-task trainer, the study group accepted an additional cost in return for the special training advantages of a cinematic visual system.

7. With respect to the selection of a remote instructor station rather than an on-board station, an inability to directly observe students' actions in the cockpit was accepted in return for increased flexibility and instructional capability.

Objective 4. The best technical approaches have been selected.

Selection of the principal technical approaches to design of the AH-64 FWS was the result of choosing between a number of opposing alternatives. These alternatives were so fundamental to the design concept as to become basic issues, which in most instances were identified at the very beginning of the study. These issues can be stated as follows:

1. An integrated cockpit versus two separate cockpits.
2. CGI versus model board visual generation system.
3. Real image versus virtual image visual display system.

4. Six-degree-of-freedom motion versus limited motion.
5. Full-mission training versus part-task training.
6. Remote instructor station versus on-board.

Most of these issues are interrelated, to the extent that it is very difficult if not impossible to identify which is most important or which must be resolved first. In the analysis phase of the study, these questions were all considered collectively by the study group before final decisions were made.

Cockpit Configuration. Early in its analysis the study group arrived at the conclusion that an integrated cockpit, in which the pilot and copilot/gunner are seated in a tandem arrangement as in the helicopter, is preferable to two separate cockpits, as long as other requirements, particularly those related to the visual system, can be met satisfactorily. With an integrated cockpit, realism is preserved and crew coordination is facilitated, although it cannot be stated that effective training involving crew coordination is not possible with separate cockpits. Perhaps the greatest advantage to an integrated cockpit is the economy achieved by not requiring a second visual system or motion system, which normally would be used with two cockpits.

The principal reason for using separate cockpits would be to permit the use of virtual image displays. (Stated another way, the use of virtual image displays requires separate, or at least, separated cockpits). Virtual image displays have certain advantages, as well as disadvantages, which are discussed below.

A compromise approach would be to use virtual image displays and separate cockpits on a single motion system, which would eliminate the cost of a second motion system. However, this is attractive only if an alternative to virtual image displays cannot be found.

A problem in any cockpit configuration using virtual image displays is how the students would enter and exit the cockpit. The field of view requirements of the visual system are so extensive that the entrance would probably have to be through the floor or from the rear.

In summary, the study group concluded that retaining an integrated cockpit should be a high priority objective of the design, subject to being able to identify a real image display system that meets the field of view, brightness, and other requirements of the trainer.

<u>Visual Generation</u>. The study group considered at great length the merits of CGI versus model board systems. The major advantages of CGI are that it provides an opportunity for variety in scenes and targets, for tactical interaction, and for realistic weapon simulation. CGI has great flexibility and exciting prospects for future growth. On the other hand, the stylized scenes require considerable user acceptance, and it is not clear that they can be used for effective training where a large amount of scene detail is important. Terrain navigation and target detection and identification are considered to be areas of training in which CGI is not very suitable.

Model boards will provide more realistic scenes than CGI up to a point, but if resolution and depth of field are improved to the extent necessary to meet the requirements of the AH-64 FWS -- the ability to acquire a target at a range of 3500 meters while hovering 6 feet above the ground, for example -- the inadequacies of the model-maker's art will become apparent.

The principal limitation of model boards is their lack of flexibility. The area covered is relatively small unless the scale is drastically reduced, which, however, would also reduce resolution and scene detail. Even with a reduced scale, the variety of topographical, natural, and cultural details that can be provided is limited. Furthermore, moving targets must be confined to fixed tracks; and weapon effects, which can be

produced by superimposing computer generated images on the CRT scene, are difficult to make realistic.

For training in terrain navigation and target detection, model boards are as unsuitable as CGI. The scene detail, while better than can be provided by current CGI technology, is still inadequate for this purpose.

A cinematic visual system is the only method of providing the scene detail and resolution adequate for terrain navigation and target detection. Such a system, however, cannot be used in interactive training situations, except in a very limited way.

The laser-scanned model board might achieve better resolution than with a TV camera and optical probe and would reduce the electrical power requirements of the conventional model board, but this technology must be considered a high risk area at the present time. Furthermore, the basic disadvantages of the model board approach -- inflexibility and limited scope -- will still remain.

The study group concluded that both CGI and model board technology have distinct limitations but that CGI is preferred because of its flexibility and potential for improvement. A cinematic system is required where scene detail is important.

Visual Display. The advantages of a virtual image display -- proven technology and good scene brightness -- were carefully considered by the study group. However, the disadvantages were considered to be overriding. Among those are the difficulty in coordinating the multi-channel displays that would be required to achieve the field of view of the AH-64. The principal disadvantage, however, is that virtual image displays dictate the use of separate cockpits, which would reduce realism and complicate coordinated crew training, as well as increase cost.

In real image displays, the study group considered several alternatives involving mixes of conventional projection systems (projection CRTs, the Eidophor projection system, GE light valves,

and Hughes liquid crystal light valves), advanced projection systems (laser scan), fixed screens, and screens attached to the motion base. The laser scan projector was discarded as involving high risk, and screens attached to the motion base were eliminated because of the necessity for limiting the distance to the screen, which would increase the problems of parallax if an integrated cockpit were used.

The final choice, a fixed cylindrical screen and a Hughes LCLV system, provides the most suitable training configuration with the best prospects for adequate brightness, low maintenance, and high reliability.

<u>Motion</u>. In analyzing the requirements for motion, the study group attempted to determine first whether all six degrees are required and, if not, which could be dispensed with. The first line of analysis was inconclusive, primarily because of lack of data; and the second could not be definitively approached since it depends on the first, although some informal opinions were obtained. Further study revealed, however, that no significant cost benefits would accrue from designing a motion system with four or five degrees of freedom rather than six. Therefore, the study group has recommended a six-post system with confidence that no better technical approach, from both a simulation and cost effectiveness viewpoint, is foreseeable.

<u>Training</u>. As described earlier in this section, the study group concluded that in those areas of training in which scene detail and resolution are important a part-task trainer, using a cinematic visual system, would be needed. The areas in question are terrain navigation and target detection and identification. Inasmuch as the inadequacies of both CGI and model board technology in these areas are well known, the soundness of the recommended approach appears to be unquestionable, if such training is to be provided at all.

It could be argued that this problem is not peculiar to the AH-64 FWS, but the counter-argument is that for AH-64 crews

no other way of performing such training is available other than in the helicopter itself. It would not be logical to provide a general purpose trainer at AH-64 units for this purpose.

Instructor Station. The study group carefully considered the merits of a remote instructor station versus an on-board station. An on-board station has the advantage, normally, of enabling the instructor to directly observe the instruments and indicators in the cockpit and to see all actions taken by the student. In addition to procedural errors, hesitations and other evidence of a student's lack of familiarity with the controls or procedures will be readily apparent. However, in the AH-64 FWS with an integrated cockpit the instructor will not be able to effectively observe the copilot/gunner from a station located behind the pilot. If a jump-seat is placed beside the copilot/gunner position (outside the cockpit) for a second instructor, he will obscure the pilot's view of the visual display. Furthermore, at either location an instructor will not be able to see the visionic displays directly and will need monitor CRT's which somewhat reduces the advantage of an on-board station. Other CRT's and input devices can be provided at an on-board station, although not easily for a jump-seat, but the number will be limited.

A remote instructor station, on the other hand, will have ample room for all desired CRT's -- for visionic display monitors, for monitors for the visual scene, and for problem control displays -- and will be able to accommodate two instructors, if desired, as well as observers. The instructor's inability to directly observe the students is not a major limitation, as demonstrated by many other trainers with remote instructor stations.

On balance, the study group concluded that an on-board instructor station is not very appropriate for the AH-64 FWS, primarily because of the integrated cockpit configuration, and

that the best technical approach would be to provide a remote instructor station with its inherent flexibility and greater training capabilities.

Objective 5. <u>The cost effectiveness of the proposed item has been determined to be favorable in relation to the cost effectiveness of competing items on a DOD-wide basis</u>.

It is estimated that the cost of operating the AH-64 FWS, in the configuration recommended by Sperry SECOR, will be approximately $60 per hour and that 4000 hours of operation per year will be generated per simulator. The cost per flying hour of the AH-64 helicopter is estimated by the AVSCOM AAH Program Office to be $836. Thus, if an hour of simulator operation replaces an hour of helicopter operation, each simulator will save $3,104,000 per year, based on fuel, maintenance, and spare parts costs alone. If the cost of building the simulator is, for example, $15 million, the cost can be amortised in 4.83 years.

The area of most significant savings is in weapon delivery. The cost of a typical load of weapons for the helicopter will be approximately $78,386. This is based on 8 Hellfire missiles at $9,000 each, thirty-eight 2.75-inch rockets at $122 each, and 500 rounds of 30-mm (inert) cannon ammunition at $3.50 each. If a simulator flies 2000 missions per year and 25 per cent of these result in full weapon expenditure, the simulator will "save" $39,193,000 in weapon costs per year. In this example, however, a simulator mission cannot be considered as replacing a helicopter mission because a corresponding number of weapon delivery missions in the helicopter would not normally be planned. However, if for every 20 simulator weapon delivery missions one similar mission in the helicopter can be saved, the annual savings per simulator will be $1,959,650 per year.

Adding the weapon-related savings to the general savings, the total will be $5,063,650 per simulator per year. With a trainer cost of $15 million, the total savings will amortise the cost in 2.96 years.

Another way of looking at savings in weapon costs is to consider the effect of using the simulator to fire the Annual Qualification Tables. The information available to Sperry SECOR indicates that the annual requirement per person will be 1 Hellfire missile, 264 2.75-inch rockets, and 1000 rounds of 30-mm ammunition. The cost of this quantity will be $44,708. If a simulator, rather than a helicopter, is used to qualify 100 pilots or CPG's, the savings will be $4,470,800 per year.

In this case, the total savings per year (weapon-related plus general savings) will be $8,574,800, reducing the amortization period to 1.75 years.

It should be noted that in a hearing before the Research and Development Subcommittee of the Senate Armed Services Committee, in May 1976, estimated amortization periods presented for a variety of simulators for the Army, Navy, and Air Force ranged from 1 year to 24, with an average of approximately 5 years. Many of these simulators represented transport-type aircraft, and the savings attributed to them did not include weapon costs.

Objective 6. The cost and schedule estimates are credible and acceptable.

The estimated cost of the AH-64 FWS is shown in Table 28, and the schedule in Table 29.

The costs are based on 1977 dollars; no allowance for inflation has been made. The costs are presented in a work breakdown structure format. The costs include design, manufacture, delivery, testing, and reliability/maintainability demonstrations for one prototype. Maintenance/operator and instructor training and normal publications are included. Contract field service, and the cost of making films for the cinematic visual system are not included.

It is considered that the above objective has been attained.

TABLE 28

30 mo

AH-64 FWS COST ESTIMATE

	Material	Labor
1.0 Trainer		
1.1 Computer (+ Programming)	$ 200,000	1,300 $ 300,000 Lo
1.2 Visual System	6,400,000	Included
1.3 Motion System	250,000	Included
1.4 Instructor Station	93,000	13,000
1.5 Trainee Station	565,000	689,000
1.5.1 Flight/Engine Controls	(54,000)	(22,000)
1.5.2 Flight/Engine Instruments	(132,000)	(40,000)
1.5.3 Weapon Delivery Systems	(291,000)	(440,000)
1.5.4 Aural, ICS, Comm, Lighting	(21,000)	(40,000)
1.5.5 Structure	(67,000)	(147,000)
1.6 Assembly and Integration	--	200,000 Lo
1.7 Part-Task Trainer	326,000	164,000
2.0 Training	--	200,000
3.0 Support Equipment	150,000	--
4.0 Logistics	500,000	Included
5.0 Test and Evaluation	--	200,000
6.0 Project Management	--	500,000
7.0 Data	--	1,300,000
8.0 Installation	--	100,000
	$12,350,000	

TABLE 29

AH-64 FWS PRODUCTION SCHEDULE

Phase	Months
Preparation for Mock-Up	0 - 3
Math Modelling	3 - 9
Program Development	3 - 12
Program Debug	12 - 18
Hardware Integration	18 - 20
Hardware/Software Integration	20 - 22
Contractor System Testing	22 - 24
In-Plant Government Testing	24 - 25½
Reliability Testing	25½ - 26
Pack and Ship	26 - 27
Installation and On-Site Contractor Testing	27 - 29
Government Acceptance Testing	29 - 30
Ready for Training	30

APPENDIX A

HELICOPTER FLIGHT SIMULATION

The block diagram of Figure A-1-1 shows the computation flow and functional dependencies among elements of a helicopter aerodynamic math model. Table A-1 defines the symbols for the variables used in the figure and in the discussion of aerodynamic equation derivation that follows.

Equations of Motion

The equations for computing linear accelerations are classical ones:

$$\dot{U}_G = \frac{X_a}{m_i} - g \sin\theta + V_G r - W_G q_1$$

$$\dot{V}_G = \frac{Y_a}{m_i} + g \cos\theta \sin\phi - U_G r + W_G P$$

$$\dot{W}_G = \frac{Z_a}{m_i} + g \cos\theta \cos\phi + U_G q_1 - V_G P$$

where

$$X_a = X_R + X_F + X_{LG} + \Delta X$$

$$Y_a = Y_R + Y_F + Y_{LG} + \Delta Y + Y_{TR}$$

$$Z_a = Z_R + Z_F + Z_{LG} + \Delta Z$$

The increments ΔX, ΔY, and ΔZ represent miscellaneous forces, such as those arising from turbulence.

Angular accelerations are computed by the equations:

$$\dot{p} = \frac{1}{I_{xx}} \left[L_a + (I_{yy} - I_{zz})\, q_1 r + J_{xz}\,(pq_1 + \dot{r}) \right]$$

$$\dot{q}_1 = \frac{1}{I_{yy}} \left[M_a + (I_{zz} - I_{xx})\, pr + J_{xz}\,(r^2 - p^2) \right]$$

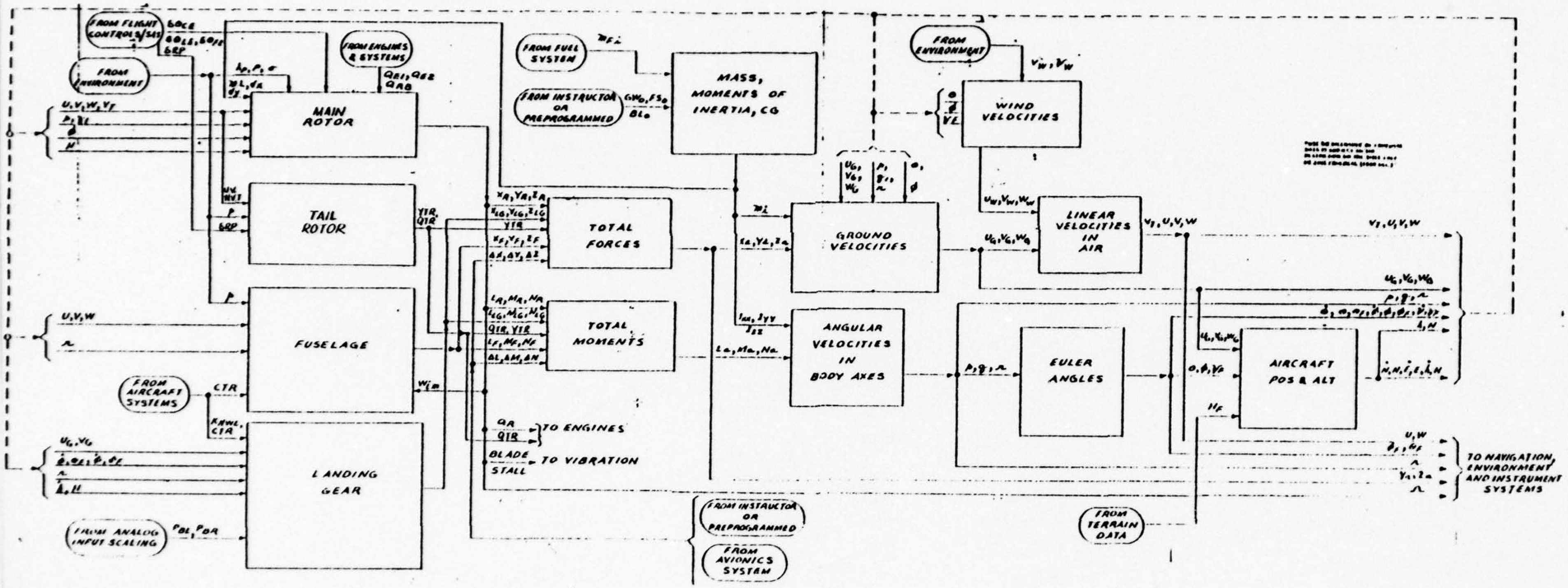


Figure AI-1. Aerodynamic Math Model Block Diagram

TABLE A-1

SYMBOLOGY

Symbol	Description
a_o	Coning angle of rotor
a_1	Longitudinal flap angle of tip-path plane with respect to no-feathering plane
a_{1s}	Longitudinal flap angle of tip-path plane with plane normal to shaft
A_{1s}	Rotor Lateral control angle
B	Blade tip loss factor
b_1	Lateral flap angle of tip-path plane with respect to control plane
b_{1s}	Lateral flap angle of tip-path plane with plane normal to shaft
B_{1s}	Rotor longitudinal control angle
BL_o	Butt line of CG
c	Effective chord of blade
CD_{AV}	Average section drag coefficient
C_L	Section lift coefficient
CTR	Index of landing gear position
dx	Longitudinal displacement of CG from references, + forward
dy	Lateral displacement of CG from reference, + forward
$\dot{E}$, E	Eastward velocity, east position of aircraft
$F_{LW}(F_{RW},F_{NW})$	Force on landing gear left (right, nose) wheel
FH_{LG}	Landing gear horizontal force, inertial system

TABLE A-1 (cont'd)

SYMBOLOGY

Symbol	Description
FS_o	Fuselage station of CG
FS_{REF}	Fuselage station of reference CG
FV_{LG}	Landing gear vertical force, inertial system
GW	Gross weight
$\dot{h}$	Rate of climb
hp	Pressure altitude
H	Height of aircraft above field
H_F	Height of field
H_R	Longitudinal in-plane force of rotor
i_{s1}	Longitudinal tilt of rotor shaft
$I_{xx}(I_{yy},I_{zz})$	Moment of inertia about X(Y,Z) axis
J_{xz}	Product of inertia
L_a	Total rolling moment
L_F	Fuselage rolling moment
L_{LG}	Landing gear rolling moment
L_R	Rotor rolling moment
L_{RH}	Rotor hub rolling moment
L_{STALL}	Rolling moment due to blade stall

TABLE A-1 (cont'd)

SYMBOLOGY

Symbol	Description
M_{f_i}	Mass of fuel in tank i
m_{STO_i}	Mass of stores at station i
M_a	Total pitching moment
M_F	Fuselage pitching moment
M_{LG}	Landing gear pitching moment
M_R	Rotor pitching moment
M_{RH}	Rotor hub pitching moment
M_{STALL}	Pitching moment due to blade stall
$\dot{N}$, N	Northward velocity, north position of aircraft
N_a	Total turning moment
N_F	Fuselage turning moment
N_{LG}	Landing gear turning moment
N_R	Rotor turning moment
$\dot{p}$, p	Rolling acceleration, rate
$P_{BL}(P_{BR})$	Pressure in left (right) brake line
P_{EO}	Engine oil pressure
P_{SL}	Barometric pressure at sea level
$\dot{q}_1$, q_1	Pitching acceleration, rate

TABLE A-1 (cont'd)

SYMBOLOGY

Symbol	Description
q_F	Dynamic pressure on fuselage
$Q_{E1}(Q_{E2})$	Engine 1 (engine 2) torque
Q_R	Rotor torque
Q_{TR}	Tail rotor torque
$\dot{r}$, r	Turning acceleration, rate
R	Radius of rotor
SHP	Shaft horsepower
S_R	Lateral in-plane force of rotor
STALL	Rotor in stall (logical variable)
S_X	Horizontal displacement of rotor hub from Z body axis (+ fwd)
T	Rotor thrust
t_o	Outside air temperature
T_o	Air temperature at sea level
U	Longitudinal air velocity
U_G	Longitudinal ground velocity
U_W	Wind velocity component along X body axis
v_w	Wind velocity
V	Lateral air velocity
V_{DD}	Drag-divergence velocity
V_G	Lateral ground velocity

TABLE A-1 (cont'd)

SYMBOLOGY

Symbol	Description
V_T	True airspeed
V_W	Wind velocity component along Y body axis
V_{xy}	Velocity in X-Y plane
W	Vertical air velocity
W''	Inflow velocity normal to no-feathering plane
W_f	Fuel flow
W_G	Vertical ground velocity
W_{im}	Average induced velocity of rotor
W_W	Wind velocity component along Z body axis
X_a	Total longitudinal force
X_F	Fuselage longitudinal force
X_{LG}	Landing gear longitudinal force
X_R	Rotor longitudinal force
Y_a	Total lateral force
Y_F	Fuselage lateral force
Y_{LG}	Landing gear lateral force
Y_R	Rotor lateral force
Y_{TR}	Tail rotor side force
Z_a	Total vertical force

TABLE A-1 (cont'd)

SYMBOLOGY

Symbol	Description
Z_F	Fuselage vertical force
Z_{LG}	Landing gear vertical force
Z_R	Rotor vertical force
$\delta\theta_{CE}$	Effective collective pitch stick deflection
$\delta\theta_{FE}$	Effective longitudinal cyclic pitch stick deflection
$\delta\theta_{LE}$	Effective lateral cyclic pitch stick deflection
δ_{RP_E}	Effective directional control pedal deflection
ΔL, ΔM, ΔN, ΔX, ΔY, ΔZ	Increments in forces and moments due to miscellaneous aerodynamic effects
$\dot{\theta}, \theta$	Pitch angular velocity, angle
θ_F	Fuselage pitch angle
θ_o	Mean pitch of rotor blade at root
ρ	Air density
σ	Air density ratio
$\dot{\phi}, \phi$	Roll angular velocity, angle

TABLE A-1 (cont'd)

SYMBOLODY

Symbol	Description
ϕ_F	Fuselage roll angle
Ψ_F	Fuselage heading angle
Ψ_w	Wind heading
Ω	Rotor rotational velocity

$$\dot{r} = \frac{1}{I_{zz}} \left[N_a + (I_{xx} - I_{yy})\, p q_1 + J_{xz} (\dot{p} - q_1 r) \right]$$

where

$$L_a = L_R + L_{TR} + L_F + L_{LG} + \Delta L$$

$$M_a = M_R + M_{TR} + M_F + M_{LG} + \Delta M$$

$$N_a = N_R + N_{TR} + N_F + N_{LG} + \Delta N$$

The increments in the moment summations have the same significance as in the force equations.

Euler Angles

The Euler angles used in coordinate conversion can be computed by the equations:

$$\dot{\phi} = p + \dot{\Psi} \sin \Theta$$

$$\phi = \int \dot{\phi} \, dt$$

$$\dot{\Theta} = q_1 \cos \phi - r \sin \phi$$

Rotor Aerodynamics

The Specific Response Approach (SRA) is characterized by a set of equations which describe helicopter rotor performance and reaction by directly computing the composite rotor forces and moments without necessitating the prior development of intermediate microparameters. In this computational system, many of the variables which are pertinent to the blade element approach, for example, simply do not exist. The tangential velocity at a given point on the blade is a necessary variable in the blade element approach and varies considerably during forward flight at different points in the rotor disc. The SRA uses what could be considered an average tangential velocity for the rotor disc ($\frac{1}{2} R\Omega$ where R is the rotor radius and Ω the rotor rotational velocity). Other quantities which the SRA does not need to compute are perpendicular velocity $U_{p\,\psi - y}$; local inflow velocity $W_{i\,\psi - y}$; local attack angle $\alpha_{\psi - y}$;

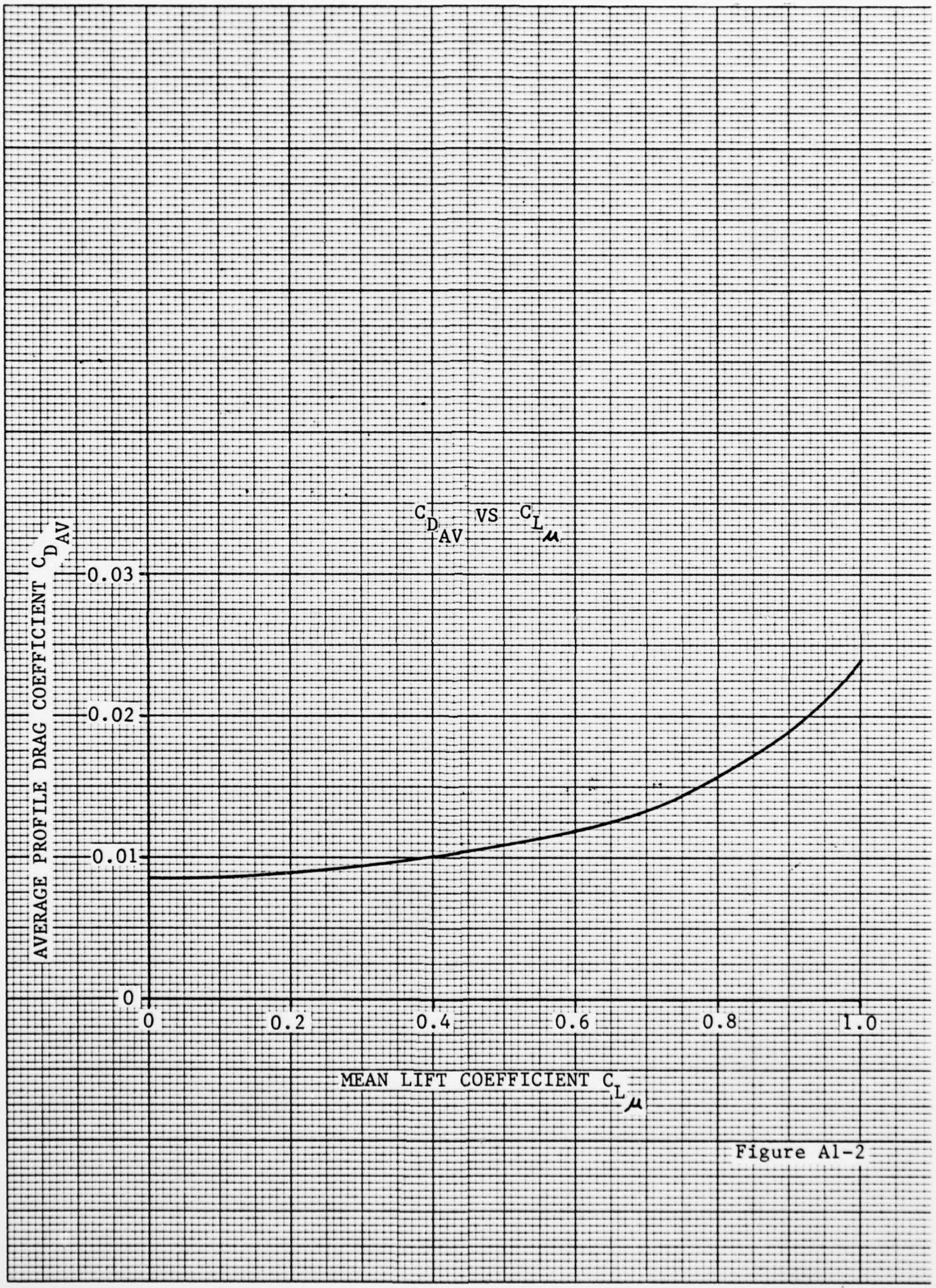
coefficient of drag $C_{D \psi - y}$; and coefficient of lift $C_{L \psi - y}$.

The SRA does not rely on local inflow computation but instead uses the mean inflow velocity, which is a direct measure of thrust. This can be easily and accurately computed. SECOR generated Revision 3 dated July 1972 to the Dynamics Report for Device 2B18 Basic Helicopter Instrument Trainer (NAVTRADEVCEN 1848-7) which showed the derivation and application of the SRA equation set for the TH-1L helicopter. This showed the generation of the mean profile drag coefficient, C_{DAV} as a function of the mean lift coefficient C_{LM}, as well as the analytical expression for computing C_{LM} for use in computing main rotor torque. Figure A1-2 shows the relationship between C_{DAV} and C_{LM} as presented in the revised Dynamics Report. Figure A1-3 is the tip speed (μ) correction factor which is applied to C_{LM}. The resulting simulation performance of the revised equation set installed in Device 2B18 was tested and found to yield in-tolerance static and dynamic results throughout the flight envelope.

The simplifying assumptions underlying the rotor simulation are that the induced velocity is uniform over the rotor disk; the slope of the curve of local lift coefficient of the blade versus local angle of attack is constant; and for a given flight condition the local drag coefficient may be replaced by an average coefficient identical for all blade sections. With these assumptions, the expressions for incremental forces are integrable along the blade and around the disk; that is, equations of the form

$$T = \frac{1}{2\pi} \int_0^{2\pi} \int_e^{BR} dt$$

have analytical solutions. The simulation equations for thrust, flap angles, induced and profile torque losses, and in-plane forces can be derived from such equations. The effects of these



$C_{D_{AV}}$ VS C_{L_μ}
AVERAGE PROFILE DRAG COEFFICIENT $C_{D_{AV}}$
0.03
0.02
0.01
0
0
0.2
0.4
0.6
0.8
1.0
MEAN LIFT COEFFICIENT C_{L_μ}

Figure A1-2

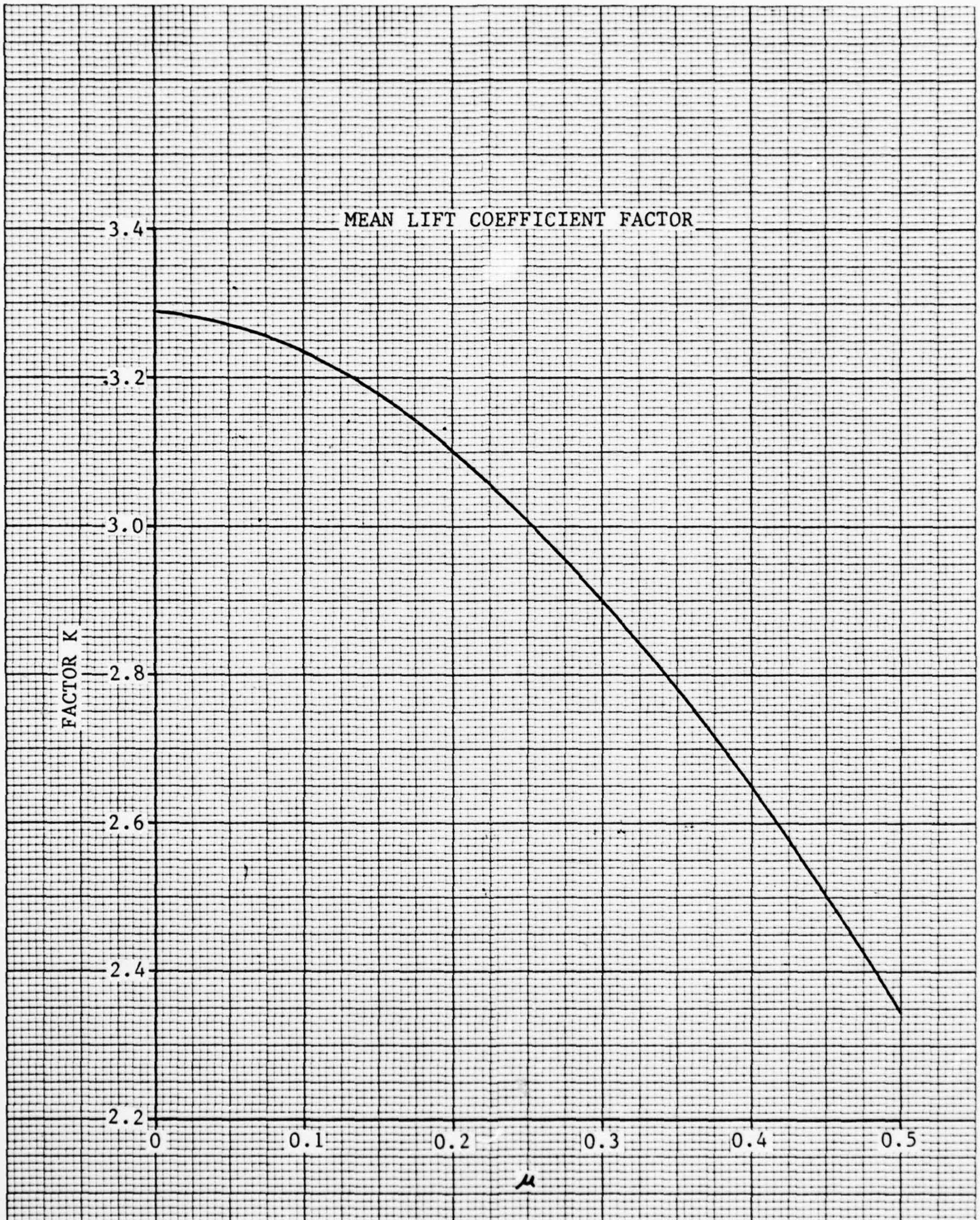

MEAN LIFT COEFFICIENT FACTOR
FACTOR K
3.4
3.2
3.0
2.8
2.6
2.4
2.2
0
0.1
0.2
0.3
0.4
0.5
μ

Figure A1-3

simplifying assumptions are discussed in the derivation of equations.

Ground effects are introduced into the thrust equation as a function of slipstream length, which is determined from forward velocity, induced velocity, and height of the aircraft above the field.

First approximations to rotor forces along the body axes are obtained by resolving thrust through the flap angles. If the resultant of all aerodynamic forces of the rotor were perpendicular to the tip-path plane, these approximations would be very close. The rotor does, however, generate in-plane forces; that is, forces parallel to the tip-path plane. The longitudinal component of in-plane forces is generally small compared with the longitudinal component of thrust, and may in some instances be neglected in the interest of computation economy. The lateral component of in-plane forces, on the other hand, is proportionately large and should be included.

Rotor moments about the body axes are the products of the aerodynamic forces along the axes and the arm through which they act on the aircraft reference center of gravity, plus moments imparted to the hub by the projection of the inertial force of flapping parallel to the shaft times the distance from the flap hinge to the center of rotation.

The derivation of the equations for rotor forces and moments begins with the expressions for the forces acting on a blade element and the resulting moments about the flapping hinge. Elementary thrust (dT), centrifugal force (dCF), inertial force due to flapping (dF), and Coriolis force (dC) are represented in Figure A1-4. A fifth force weight, is not shown. Moments about the flapping hinge corresponding to these forces are expressed as follows:

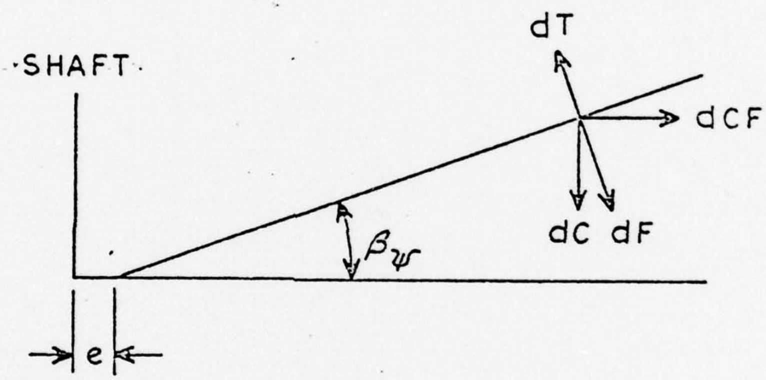


FIG. A1-4 FORCES ON ROTOR BLADE ELEMENT

Moment of flapping force $-\int_e^R \ddot{\beta}_\Psi mr^2\, dr$

Moment of centrifugal force $-\int_0^R \beta_\Psi \Omega^2 mr^2\, dr$

Moment of Coriolis forces $-\int_0^R 2\Omega(q_1 \sin\Psi - p\cos\Psi)$

$mr^2\, dr$

Thrust moment $+\int_e^{BR} r\, dT$

Static Moment $-\int_0^R mgr\, dr$

Let $\int_e^R mr^2\, dr = \int_0^R mr^2\, dr = I_B$ and $\int_0^R mr = M_B r_B$.

Then

$$- I_B\ddot{\beta}_\Psi - I_B\Omega^2\beta_\Psi - I_B 2\Omega(q_1 \sin\Psi - p\cos\Psi)$$

$$- M_B r_B\, g + \int_e^{BR} r\, dT = 0$$

The particular solution to this equation is a Fourier series

$$\beta\Psi = a_o - \sum_{n=1}^{\infty} (a_n \cos n\Psi + b_n \sin n\Psi)$$

Practical experience has demonstrated that the flap angle can be represented with acceptable accuracy by the first three terms of this series:

$$\beta\Psi = a_o - a_1 \cos\Psi - b_1 \sin\Psi$$

The moment equation can be simplified by expressing differentiation with respect to time as differentiation with respect to the angle Ψ (which equals Ωt) and then substituting the truncated Fourier series for $\beta\Psi$.

Since

$$\ddot{\beta} = \Omega^2 (a_1 \cos\Psi + b_1 \sin\Psi)$$

the moment equation takes the form

$$-I_B \Omega^2 a_o - 2I_B (q_1 \sin\Psi - p \cos\Psi) - M_B r_B g + \int_e^{BR} r \, dT = 0$$

Solution of this equation for the Fourier coefficients now depends on deriving an integrable expression for elementary thrust involving these coefficients. Such an expression will first be developed for a rotor with an untwisted blade and no cyclic variation in pitch and then modified for a rotor system which has both twist and cyclic variation in pitch.

By classic aerodynamic theory, elemental thrust $dT = q\, C_L dS$, where q is the dynamic pressure, C_L the lift coefficient of the element, and dS the area of the element. Set $q = \frac{1}{2}\rho U_E^2$ and set $dS = c\, dr$, where U_E is the velocity of air acting on the blade element, c the blade chord, and r the distance of the element from the center of rotation. Then

$$dT = \tfrac{1}{2} \rho\, c\, C_L\, U_E^{2}\, dr$$

The velocity U_E of the air acting on the blade element can be resolved into two components U_T and U_p lying along coordinate axes in a plane perpendicular to the blade axis, as shown in Figure A1-5.

$$U_T = \Omega r + U \sin\Psi + V \cos\Psi$$

$$U_p = W' - (r-e)\dot{\beta}\Psi - \beta\Psi (U \cos\Psi - V \sin\Psi) + r (q_1 \cos\Psi + p \sin\Psi)$$

where $W' = W - W_i$

Since W_i cannot be defined with an acceptable degree of accuracy, we assume that it is uniform over the disk, i.e., $W_i = W_{im}$.

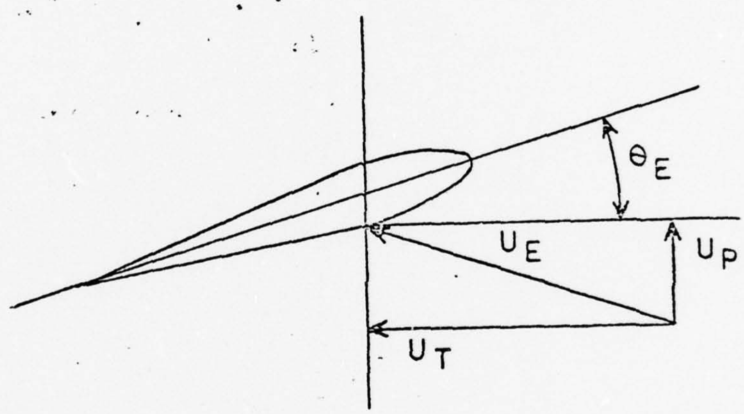


FIG. A.1-5 BLADE ELEMENT VELOCITIES

Over most of the velocity regime C_L is a linear function of blade element angle of attack α_E; that is, $C_L = a\alpha_E$, where a is constant and

$$\alpha_E = \theta_E + \tan^{-1}\frac{U_P}{U_T} \cong \theta_E + \frac{U_P}{U_T}$$

At the higher airspeeds at which flow separation occurs, however, the section lift coefficient C_L decreases with α_E, while section drag increases sharply. The problem of flow-separation effects had to be dealt with early in the development of the Specific Response Approach. The decision was made to assume that section lift varied linearly with α_E and that an average drag coefficient could be used for all sections; compute performance and flying qualities on the basis of these assumptions; compare the results with data; and, finally, determine the magnitude of the errors and the nature of correction factors that would compensate for them.

Two facts argued for this approach: 1) α_E itself cannot be defined precisely because it is a function of local induced velocity, for which no adequate expression has been developed; and 2) thrust, according to the momentum theory, is a function of mean induced velocity. The premise was that the assumptions of uniform induced flow and linearity of C_L, and the use of an average section drag coefficient, together would produce smaller errors in rotor forces and moments than those inherent in other approaches, which depend heavily on accurate representation of local induced velocity. Furthermore, the simple expressions for forces and moments that would result, with cross-coupling and other effects clearly displayed, would be susceptible to modification by correction factors if they should be needed.

Proceeding as outlined above, SECOR has to date constructed accurate models of the HH-3F, HH-52A, CH-3E, HH-53C, and TH-1L helicopters. In the development of these models it was found

that where the effects of flow separation are perceptible, they can be compensated for by two measures: 1) applying a correction factor to the profile power losses as a function of excess of airspeed over the drag-divergence velocity; and 2) in simulators equipped with a motion system, introducing the vibratory and other effects of stall into that system. The correction for drag divergence is discussed in the derivation of the equation for main rotor torque. The velocity at which stall effects are incipient is determined directly from flight manual stall charts.

Letting $C_L = a\alpha_E$, then, and setting $U_E = U_T$, the equation for elemental thrust can be written:

$$dT = \tfrac{1}{2}\rho \, ac \, (\Theta_E U_T^2 + U_T U_P) \, dr$$

With the expansion of the terms in parentheses and the substitution of $\beta\Psi = a_0 - a_1 \cos\Psi - b_1 \sin\Psi$ and $\dot{\beta}\Psi = \Omega (a_1 \sin\Psi - b_1 \sin\Psi)$ we have an expression such that dT (and hence r dT) is integrable along the blade and around the disk. The result of the integration, $\int_e^{BR} r \, dT$ is substituted in the equation for moments about the flapping hinge. The functions of double angles are discarded and the remaining terms are collected to yield the free term, the coefficient of $\sin\Psi$, and the coefficient of $\cos\Psi$. The free term, set to zero, can be solved for the mean flapping angle, or coning angle, a_0. The coefficients of $\sin\Psi$ and $\cos\Psi$, set to zero, can be solved for a_1 and b_1, respectively.

With the integration of the elemental expression dT along the blade and around the disk the average thrust per blade is obtained. The total thrust (less ground effects) is then the product of the number of blades and the average thrust per blade:

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AH-64 FLIGHT AND WEAPONS SIMULATOR CONCEPT FORMULATION STUDY. V--ETC(U)

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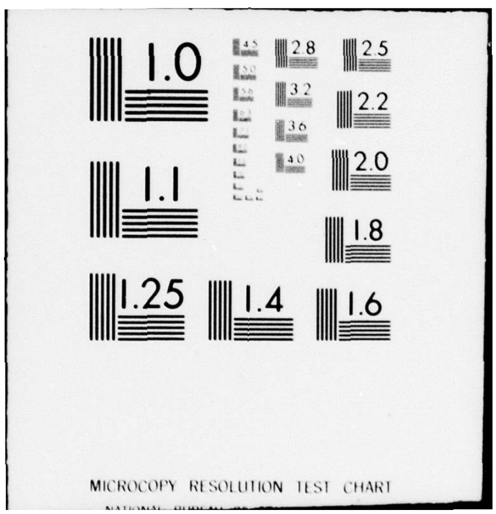
1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
MICROCOPY RESOLUTION TEST CHART

$$T = \frac{b}{2\pi} \int_0^{2\pi} \int_e^{BR} \frac{dT}{dr}\, dr\, d\Psi$$

Since $\int_0^{2\pi} \sin\Psi = \int_0^{2\pi} \cos\Psi = \int_0^{2\pi} \sin\Psi \cos\Psi = \int_0^{2\pi} \sin^2\Psi$

$\cos\Psi = \int_0^{2\pi} \sin\Psi \cos^2\Psi = 0$, the final equation for total thrust is relatively simple; most of the terms of the expansion of the elemental expression vanish in integration around the disk.

Ground effects are introduced as a function of slipstream length L_{ss}, which is determined from forward velocity, induced velocity, and the height of the craft above the field.

The final form of the thrust equation is:

$$T = \sigma \left[\Theta_E \left(k_1 \Omega^2 + k_2 V_{xy}^2\right) + k_3 W' + k_4 \left(p U + q_1 V\right) \right] f(L_{ss})$$

The constants depend only on the physical characteristics of the blade. The term $k_4 (p U + q_1 V)$ is generally so small that it is eliminated from the thrust equation.

The preceding equations for thrust and flap coefficients were based on a rotor system with an untwisted blade and no cyclic variation in pitch. Where blade has a twist distributed linearly along the blade, the blade element pitch $\Theta_E = \Theta_o + K(r)$, where Θ_o is the blade pitch at the root. This expression for Θ_E can be substituted in the thrust equation before integration. Where twist is linear, it has proved quite accurate to consider Θ_E as the pitch at a distance of 0.75R from the center of rotation; that is, for Θ_E the substitution Θ_{75} is made where $\Theta_{75} = \Theta_o + .75x$ total twist.

The root blade pitch angle at each azimuth location around the rotor disk depends on the effective control settings developed by the flight control system. The pitch at the root

of the blade varies cyclically according to the expression:

$$\Theta = \Theta_0 - A_{1s}\cos\Psi - B_{1s}\sin\Psi$$

Flap coefficients for a rotor with cyclic pitch change are developed in exactly the same way as for a rotor with constant pitch. They are derived with respect to the no-feathering plane of the rotor, however; that is, they are developed with respect to the plane of constant pitch rather than with respect to the plane perpendicular to the shaft. The inflow velocity into the no-feathering plane has components of forward and side velocities approximately equal to $U\,B_{1s} + V\,A_{1s}$. To distinguish this inflow velocity from W', the inflow velocity for the rotor with constant pitch, it is represented by:

$$W'' = W - W_{im} - U\,B_{1s} - V\,A_{1s}$$

The substitution of W" for W' in the thrust and flap equations yields the thrust, and the coefficients of flapping with respect to the no-feathering plane, of the rotor with cyclic pitch change.

The relationship between the flap angles with respect to the no-feathering plane and the flap angles with respect to a plane perpendicular to the shaft is illustrated in Figure A1-6. Note that:

$$a_{1s} = a_1 - B_{1s}$$

$$b_{1s} = b_1 + A_{1s}$$

The angle B_{1s} is conventionally measured positive counterclockwise from the plane perpendicular to the shaft; the angles a_1 and b_1, positive clockwise from the no-feathering plane, the angles A_{1s}, a_{1s} and b_{1s}, positive clockwise from the plane perpendicular to the shaft.

Rotor torque is computed as $(550/\Omega)\ SHP_R$. In the SRA approach SHP_R is taken as the sum of the individual power-absorbing elements:

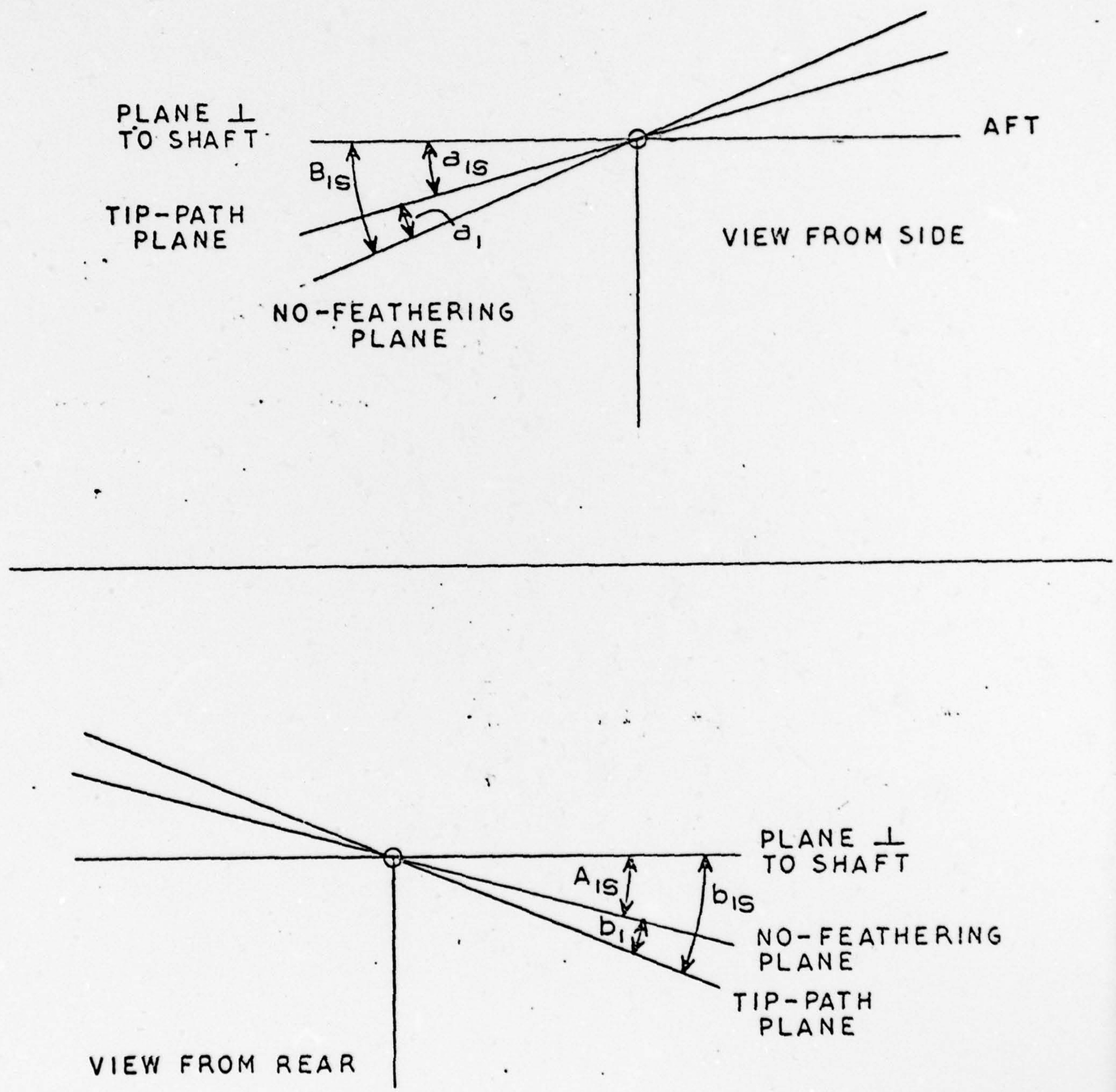

FIG. A1-6 FLAP AND CONTROL ANGLES

$$Q_R = \frac{550}{\Omega}(hp_p + hp_i + hp_o + hp_c + hp_{acc})$$

where:

hp_p = power to overcome parasite drag

hp_i = power to overcome induced drag

hp_o = power to overcome profile drag

hp_c = power to climb

hp_{acc} = power to accelerate

The parasite drag element hp_p is computed by

$$hp_p = \frac{\text{Drag x } V_{xy}}{550} + \frac{1}{2}\rho V_{xy}^3 C_D f$$

In this expression f is the equivalent flat-plate area of the helicopter. Setting $k_1 = \frac{1}{2}\rho_o C_D f$,

$$hp_p = k_1 \sigma V_{xy}^3$$

The power to overcome induced drag is simply

$$hp_i = T W_{im}/550 = k_2 T W_{im}$$

To determine the power to overcome profile drag, the mean profile drag coefficient C_{DAV} is derived as a function of thrust and forward velocity. Then

$$hp_o = \frac{bc \rho C_{DAV} R (\Omega R)^3}{4400} \left(1 + \frac{4.65 V_{xy}^2}{\Omega^2 R^2}\right)$$

The term $4.65 V_{xy}^2/(\Omega^2 R^2)$ is included to account for radial flow. Simplifying,

$$hp_o = k_3 \sigma C_{DAV} (\Omega^2 + k_4 V_{xy}^2)$$

Power to climb is

$$hp_c = T \dot{h}/550 = k_2 T \dot{h}$$

Power to accelerate is

$$hp_{acc} = m_i \dot{V}_T/550$$

Combining terms,

$$Q_R = \frac{550}{\Omega} \left\{ k_1 \quad V_{xy}^{\ 3} + k_2 \left[T\ (W_{im} + \dot{h}) + k_3 \rho\ C_{DAV} \right.\right.$$

$$\left.\left. (\Omega^2 + k_4\ V_{xy}^{\ 2} + m_i\ \dot{V}_T\ V_T \right] \right\}$$

This equation must be modified to include the effects of drag divergence. The forward velocity at which drag divergence occurs is derived as a function of thrust and pressure altitude. The rotor shaft horsepower requirements are computed with the foregoing equations for a range of forward airspeeds, gross weights, rotor angular velocities, pressure altitudes, and rates of climb, and summed with other system losses. Values of total shaft horsepower required are plotted directly on aircraft performance curves. A correction factor may be added to the expression for profile drag to bring the computer curves into final congruence with the curves of actual performance. The correction factor has the form $1 + k_5\ f(V_{xy} - V_{DD})$ where k_5 is 0 if $V_{xy} < V_{DD}$, and $k_5 = 1$ if $V_{xy} \geq V_{DD}$.

The modified equation for torque is:

$$Q_{R_1} = \frac{550}{\Omega} \left\{ k_1 \sigma\ V_{xy}^{\ 3} + k_2 \left[(W_{im} + \dot{h}) + m_i\ \dot{V}_T\ V_T \right] \right.$$

$$\left. + k_3 \sigma\ C_{DAV} \cdot (\Omega^2 + k_4\ V_{xy}^{\ 2}) \left[1 + k_5\ f(V_{xy} - V_{DD}) \right] \right\}$$

The calculation of mean induced velocity is based on the momentum theory. According to this theory the mean induced velocity at hover is

$$W_{im_o} = \frac{T}{2 \pi \rho\ (BR)^2}$$

Variation of W_{im} with airspeed is essentially linear over a portion of the speed regime but nonlinear at transition and high airspeeds. The functional relationship $W_{im}/W_{im_o} =$

$f_1(V_{xy}/W_{im_o})$ is indicated in the lower portion of Figure A1-7.

Also shown on Figure A1-7 is a correction factor accounting for non-uniform flow and slipstream rotation. This factor, too, is a function, f_2, of V_{xy}/W_{im}. In the SRA simulation the two functions are combined to form a single function

$$f(V_{xy}/W_{im_o}) = f_1(V_{xy}/W_{im_o})\ f_2(V_{xy},\ W_{im_o})$$

which is then fitted with straight-line segments for representation in the digital computer. In the real-time simulation program $f(V_{xy}/W_{im_o})$ is generated by linear interpolation. The expression for mean induced velocity, then, is

$$W_{im} = W_{im_o}\ f(V_{xy}/W_{im_o})$$

If the resultant of all aerodynamic forces were perpendicular to the tip-path plane of the rotor, the longitudinal and lateral forces of the rotor would be represented exactly by resolving thrust (T) through the flap angles with respect to the plane perpendicular to the shaft:

$$X_R = -T \sin a_{1s}$$

$$Y_R = T \sin b_{1s}$$

Besides thrust, however, the rotor generates forces parallel to the tip-path plane, and these forces, while generally small compared with the projections of the thrust vector, can be taken into account to refine the equations given above.

The longitudinal and lateral in-plane forces, H_R and S_R respectively, are derived by integrating along the blade and around the disk the elemental expressions

$$dH_R = dD \sin\Psi - dT\ a_o \cos\Psi$$

$$dS_R = -dD \cos\Psi - dT\ a_o \sin\Psi$$

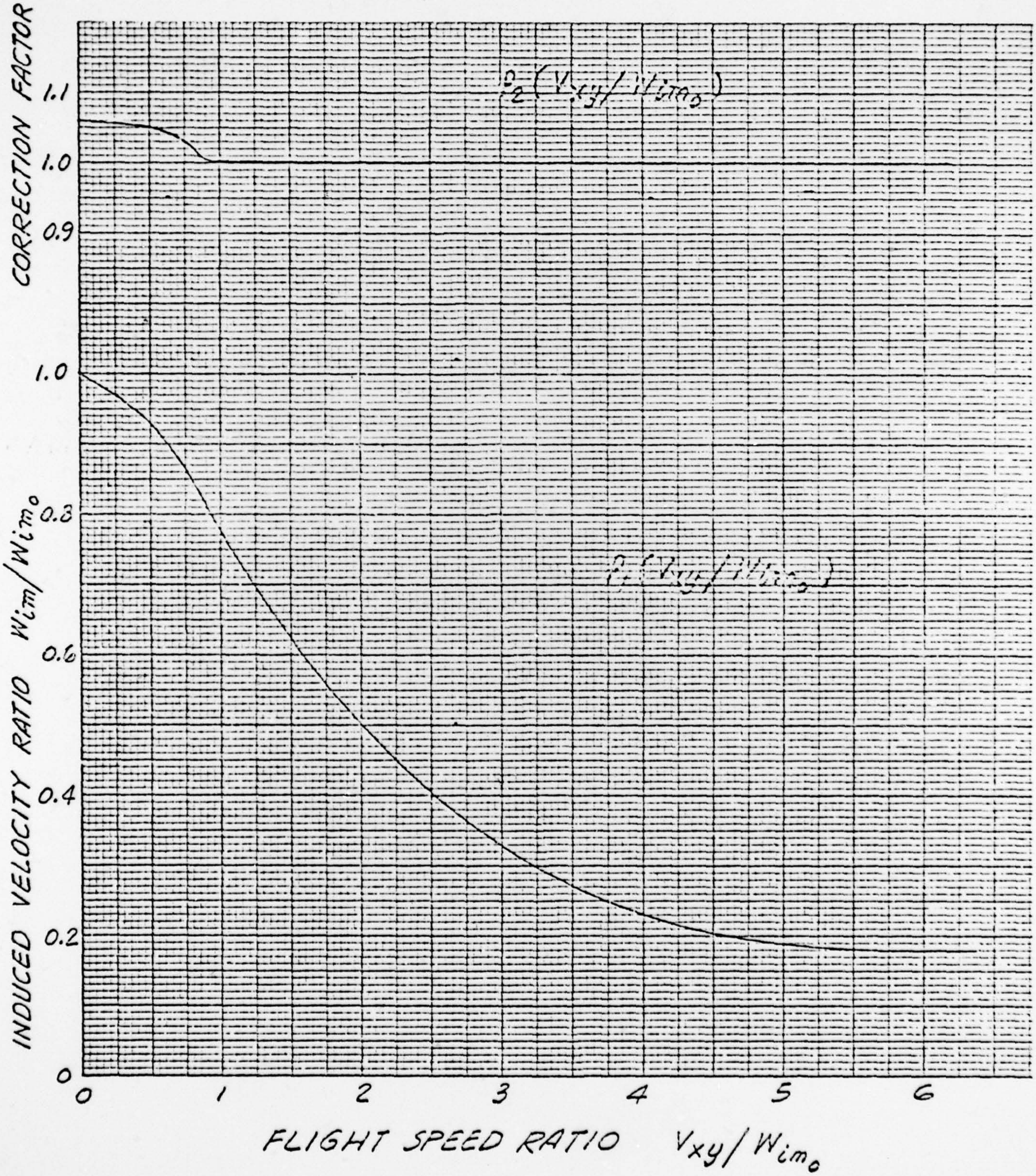

FIG. A.1-7 INDUCED VELOCITY RATIO VS. FLIGHT SPEED RATIO

where

$$dD = -\frac{1}{2}\rho c \left[U_T^2{}_{(TP)} C_{DAV} - a \left(\Theta_{TP} U_{T(TP)} U_{P(TP)} + U_{P(TP)}^2 \right) \right]$$

and dT is as previously given.

In this equation dD is the elemental drag; Θ_{TP} is the effective blade pitch relative to the tip-path plane; U_T and $U_{T(TP)}$ are the velocity components of the wind on the element in the tip-path axes; and C_{DAV} is the average drag.

$$\Theta_{TP} = = \Theta_E - a_1 \sin\Psi + b_1 \cos\Psi$$

$$U_{T(TP)} = U_T$$

$$U_{P(TP)} = U_P + U_T (a_1 \sin\Psi - b_1 \cos\Psi)$$

The average section drag C_{DAV} is computed as a function of thrust and forward velocity as described in the discussion of main-rotor torque. The elements dH_R and dS_R are expanded and integrated along the blade and around the disk to get the average in-plane forces generated by the rotor.

The total rotor force along each body axis is the sum of the projection of thrust and the in-plane force on that axis. With use of the small-angle assumption for a_{1s} and b_{1s}, the expressions for longitudinal and lateral forces become

$$X_R = -T a_{1s} + H_R$$

$$Y_R = T b_{1s} + S_R$$

The positive direction of the Z body axis is downward, so that

$$Z_R = -T$$

The aerodynamic forces just defined, acting through the distances dx, dy, and S_z, create moments about the X, Y and Z axes. In addition, certain moments are imparted to the hub

as the result of forces acting through the arm e, which is the distance of the flapping hinge from the center of rotation. One of these is the inertial force of blade flapping. Projected parallel to the rotor shaft, it creates longitudinal and lateral moments at the hub defined by

$$M_{RH} = b\, M_B r_B\, e \frac{1}{2\pi} \int_0^{2\pi} \ddot{\beta}_\Psi \cos\Psi \; d\Psi$$

$$L_{RH} = b\, M_B r_B\, e \frac{1}{2\pi} \int_0^{2\pi} \ddot{\beta}_\Psi \sin\Psi \; d\Psi$$

With respect to the shaft plane, β_Ψ is expressed by

$$\beta_\Psi = a_o - a_{1s} \cos\Psi - b_{1s} \sin\Psi$$

so that

$$\ddot{\beta}_\Psi = \Omega^2 \left(a_{1s} \cos\Psi + b_{1s} \sin\Psi\right)$$

With integration as indicated

$$M_{RH} = \frac{1}{2} M_B r_B\, e\, b \Omega^2 a_{1s}$$

and

$$L_{RH} = \frac{1}{2} M_B r_B\, e\, b \Omega^2 b_{1s}$$

Total moments generated by the main rotor are summarized as follows:

$$L_R = -Y_R S_Z + T\, dy + L_{RH}$$

$$M_R = X_R S_Z - T\,(dx + S_x) + M_{RH}$$

$$N_R = Q_{MR} + X_R\, dy - Y_R\,(dx + S_x)$$

Figure A1-8 shows the interrelationship of all the rotor equations in block diagram form.

<u>Fuselage/Wing</u>

Approximations to the aerodynamic forces and moments of the fuselage/wing are computed in the conventional manner from

wind-tunnel data. Wind-tunnel data for helicopters, however, is rarely refined enough for simulation accuracy. It seldom includes downwash effects, and it is occasionally taken on a model with structural features differing from those of the production aircraft. In static solutions of the simulation model, errors in wind-tunnel data manifest themselves as errors in aircraft attitude and control deflection. For fidelity of simulation, a good approximation of downwash effects on the fuselage/wing combination is required.

Since wind-tunnel data is generally presented in terms of the stability axis system, fuselage forces and moments will be computed along and about the stability axes and then transformed into the body system.

Ground Handling

Forces and moments imparted to the helicopter on the ground by rolling friction, application of brake pressure, and landing-gear compression occur in the inertial system. Ground-handling forces must be transformed into the body system for summation with other forces and moments as indicated in the summation equations on Figure A1-1.

Other Aerodynamic Effects

Aerodynamic effects of external stores, acting through arms defined by the stores, location with respect to the helicoper CG, will generate increments in the total forces and moments acting on the helicopter. These must be updated as stores are loaded and released.

APPENDIX B

The following persons made the principal contributions to this report:

Joseph L. Dickman, Sperry SECOR
Howard Kestenbaum, Sperry Systems Management
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